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COATINGS FOR LIGHTING PROTECTION OF STRUCTURAL REINFORCED PLASTICS

J. T. Quinlivan
C. J. Kuo
R. O. Brick

TECHNICAL REPORT AFML-TR-70-303 Pt. I

March 1971

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FOREWORD

This report was prepared by The Boeing Company, Seattle, Washington, under U.S. Air Force Contract No. F33615-69-C-1612 and catalogued as Boeing Document No. D6-25479. This contract was initiated under Project No. 7340, "Nonmetallic and Composite Materials", Task No. 734007, "Coatings for Energy Utilization, Control and Protective Functions". The work was administered under the direction of the Nonmetallic Materials Division, Air Force Materials Laboratory, with Captain J. G. Breland and Mr. James Weaver as the project engineers.

The research was conducted by the Electrodynamics Technology and the Materials Technology of the Commercial Airplane Group of The Boeing Company from 15 May 1969 to 15 November 1970. Mr. R. W. Sutton was Program Manager and Mr. R. O. Brick was Principal Investigator. Those assisting were Messrs. C. J. Kuo and S. D. Schneider of Electrodynamics Technology; Dr. J. T. Quinlivan of Materials Technology, Messrs. L. Hopp and L. Dolan of Lightning Laboratory; and Mrs. G. Gilman and Mr. R. Hodges of Material Laboratory.

This report was submitted by the authors on November 15, 1970.

This report has been reviewed and is approved.

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ABSTRACT

Coatings and coating systems were developed for protection of boron and graphite fiber reinforced plastic composites from structural damage by lightning strikes. The effectiveness of the protective capability of the proposed coating systems was tested with an artificial lightning stroke consisting of both high current and high coulomb components. The primary criterion of a successful coating was the capability of a test panel to sustain a simulated lightning discharge without structural damage to the composite substrate.

Numerous coatings or coating systems have been developed and evaluated. They can be classified into the following general categories: continuous metal foils; woven metal wire fabrics; knitted metal wire mesh; plasma and flame sprayed aluminum; metal pigmented paints; and nonmetallic pigmented paints with or without undercoatings. Several coating systems show protective capability with aluminum knitted wire mesh and aluminum woven wire fabric considered to be the most promising coatings.

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SECTION I

INTRODUCTION

Natural lightning attachment to an aircraft is not an improbable event. Based on pilot reports, it is estimated that each military and civilian aircraft is struck an average of once a year. Since little can be done to prevent lightning strike attachment to aircraft, protection techniques have been developed to ensure that lightning does not adversely affect aircraft flight or cause excessive maintenance damage.

The lightning protection of the first generation of aluminum aircraft was relatively uncomplicated. The basic all-metal riveted airframe provided inherent shielding that adequately protected personnel and equipment from the detrimental effects of lightning. As aircraft became more sophisticated, lightning protection became more complex due to the increased use of nonmetallic sections such as radomes, fairings, access panels, and secondary structure.

Lightning protection for these nonmetallic sections evolved over the years into a number of protection schemes, among which are expendable metal strips, metal or carbon black pigmented paints, and plasma or flame sprayed aluminum. All of these techniques depend on the dielectric integrity of the basic panel for their protection effectiveness, and therefore, are acceptable for conventional homogeneous dielectrics. Panels or aircraft members consisting of epoxy matrices structurally reinforced with boron or graphite fibers are not dielectrically homogeneous and for that reason present new problems in lightning protection.

The dielectric integrity of high modulus composites is degraded due to the highly conductive tungsten core of the boron fiber and the high conductivity of the graphite fibers. When laminated in a plastic matrix, these conductive fibers are in close proximity to one another and to the panel surface and result in a conductive array that provides numerous arc breakdown paths which shunt lightning currents into and through the panel. Unless precautions are taken, lightning can cause large holes and delaminations at the attachment point and may create further damage as the lightning currents pass through the composite structure. Studies by General Electric and the Philco-Ford Company have indicated that several amperes of pulse current through boron fibers can cause a drastic reduction in fiber strength without evidence discernable to the naked eye. High levels of lightning current can be expected to flow through fibers that are not protected from lightning. In boron epoxy laminates the damage mechanism is primarily filament breakage while in graphite epoxy laminates it is primarily resin pyrolysis at the fiber-matrix interface.

A study program was initiated to develop coatings or coating systems that can be applied by conventional techniques to the exterior surface of boron fiber and graphite fiber reinforced plastics, such that:

A. The coating or coating system will minimize or eliminate the damage at the stroke attachment point.

B. The coating or coating system will provide an adequate path for lightning currents, thereby preventing the flow of detrimental electrical currents into the plastic matrix or its reinforcing fiber.

C. The coating or coating system will be resistant to moisture, fuels, lubricating and hydraulic oils and the normal environment of operational aircraft.

Artificial lightning discharges were used to assess candidate systems for their protection effectiveness. The investigation was conducted in the following phases:

Phase I — The developmental formulation of coatings suitable for potential lightning protection of boron fiber and graphite fiber reinforced epoxy plastic composites.

Phase II — Preliminary laboratory evaluation and screening of the protection offered reinforced plastics from lightning discharges by the coatings developed under Phase I.

Phase III — Final evaluation of the most promising coatings developed under Phase II.

SECTION II

SUMMARY

The evaluation of coatings and coating systems was conducted by directing artificial lightning discharges to coated composite panels. The composite substrates for screening purposes were 6 x 12 inches, five ply laminates. Final lightning test evaluation utilized thicker, 1 foot square laminates.

The lightning discharge simulator consists of a capacitor bank, a battery bank, and associated switching circuits. The capacitor bank with a total capacitance of 42 microfarads rated at 30 KV is composed of eight capacitors, and the battery bank is built with 72 twelve-volt storage batteries in a series and parallel configuration. The required test discharges are generated by switching the two banks at appropriate time periods.

Numerous coatings or coating systems were formulated, developed and tested. Research effort involving coatings was concerned with defining the minimum thickness of continuous aluminum foil which would provide effective lightning protection for advanced composites. The effects of high dielectric strength insulating layers on metal foil coating effectiveness were also determined. Other coatings were rated relative to the results obtained on these model systems. Coatings have been found which provide protection to the same degree as comparable thicknesses of aluminum foil. High dielectric strength insulating layers were found to improve significantly the protective qualities of most coatings.

Several studies involving metal pigmented paints were carried out. Silver and specially treated copper metal pigments provide electrical conduction by particle-to-particle contact. These provide lightning protection to composites when sufficient coating thicknesses are maintained. Other metal pigments, such as aluminum and copper, are poor conductive coatings and do not provide lightning protection to advanced composites. These coatings will provide lightning protection for glass fiber reinforced composites, however.

Nonmetallic pigments have also been investigated. Conductive carbon blacks are not substitutes for silver, but can be tailored to provide a moderate degree of lightning protection; these systems must employ expendable metal strips in conjunction with an insulating layer between the composite and the coating. Other paints have also been found to provide lightning protection. These are unpigmented and pigmented epoxy systems and can provide excellent protection at very severe discharge levels.

Plasma and flame sprayed aluminum coatings also offer efficient lightning protection. These coatings provide continuous metal coverage of the composite surface and possess excellent electrical properties. High application costs are associated with this type of coating.

The most promising coatings employ knitted wire mesh or woven wire fabric as the conductive member. Such materials are easily impregnated with resin and can be incorporated into the composite at the time of manufacture. Aluminum wire has been found to be the most suitable for this application in terms of its light weight and high electrical conductivity. It was observed that materials with metal densities equivalent to 1.5-mil of aluminum provided excellent protection. The study of large open area wire mesh and high coverage wire fabrics is described. These were investigated to determine the effects of such variables on lightning protection characteristics.

An exploratory development effort on these metal wire containing coatings has demonstrated excellent potential for these systems. Difficulties remaining to be overcome are limited to the sources and cost of the wire materials themselves. It can be confidently predicted that these can be overcome to provide an excellent lightning protection scheme inexpensively, at a minimum weight increase and with at least the environmental characteristics of the resin matrix of the composite. A plan to provide this development has been formulated.

From the experimental results, it is found that only the composite panel coated with fine mesh aluminum fabric provides reasonable electromagnetic shielding capability, and it can be extrapolated that the induced current on a single boron fiber will be 1.4 amp or less and on a graphite fiber will be 7 ma or less at a 200 KA discharge.

SECTION III

MATERIALS AND PROCESSES

3.1 TEST PANELS

The test panels employed in the screening phases of this study were 6-inch by 12-inch flat laminates. The boron fiber and graphite fiber laminates consisted of five plies in an alternating 0-90° orientation. Nearly all panels were such that the fibers in the outer ply were oriented along the 12-inch direction. In addition, two unidirectional, five ply laminates were prepared. These contained fibers oriented along the 12-inch panel dimension. The glass fabric reinforced control laminates were constructed from thirteen plies of 181E style fabric.

Final screening tests employed 12-inch square flat laminates. These are constructed from 14 plies of graphite in a 0, 90, 0, 90, 0, 90, 0, 0, 90, 0, 90, 0, 90, 0 orientation or 16 plies of boron in a 0, 90, 0, 90, 0, 90, 0, 90, 90, 0, 90, 0, 90, 0, 90, 0 orientation. The glass fabric laminates were fabricated from 13 plies of 181E style fabric.

3.1.1 Filament and Fiber Reinforcement

The boron filament and graphite fibers used in this program were supplied by the Air Force Materials Laboratory.

The boron filament employed was received from the 3M Company in the form of a prepreg tape with the filaments unidirectionally oriented along the length of the tape. These filaments were manufactured by the Hamilton Standard Division of United Aircraft Corporation. The filaments are prepared by depositing a boron coating over a 0.0005-inch diameter tunsten wire substrate. During this process a chemical reaction occurs and portions of the substrate are converted from tungsten to tungsten borides. The DC resistivity of boron filaments is 2600 micro-ohm-cm (1). The drawn tungsten wire precursor has a resistance of about 7 micro-ohm-cm at 0.01-0.02 mm diameter (0.0005 inch = 0.0127 mm) (2). Thus, the core material of the filaments has reacted at least partially with boron. Microscopic evidence of this is given in Section 5.2. These studies have also shown the boron filaments to be somewhat porous and non-uniform.

"Thornel" graphite yarn was also employed as a high modulus reinforcement. Thornel is a continuous yarn of 2-ply construction with 720 filaments per ply. The average filament diameter is 6.6 microns (0.00026 inch). Typically, these fibers had a tensile modulus of 50 million psi (MSI), although lot-to-lot variations from 46.0 MSI to 55.0 MSI were observed. High modulus carbon based fibers of this modulus have a resistivity of about 1060 micro-ohm-cm (3).

Style 181E glass fabric was employed as the reinforcement for the control material.

3.1.2 Resin Materials

"Scotchply" SP-272 is a high temperature epoxy resin manufactured by the 3M Company. The resin was used for all of the boron composite work reported herein. The boron/epoxy composites were cured in an autoclave at 350°F for one hour minimum under 85 psi. The laminates were post-cured in an air circulating oven for 4 hours at 350°F. The filament volume content was typically 48-53 percent.

American Cyanamid BP-907 epoxy resin was chosen for the graphite matrix. This resin was cured according to the instructions of the manufacturer (90 minutes at 350°F). Common vacuum bag procedures were employed. The filament volume content of the graphite composites was typically 45-50 percent.

Resins conforming to the Boeing Material Specification (BMS) 8-79J were employed for the glass fabric reinforced control panels. This specification relates to preimpregnated material consisting of 181 or cetain other glass fabric reinforcement with a rigid thermosetting epoxy resin matrix. The material was cured in an autoclave at 260°F for 90 minutes. Production qualified materials were employed.

3.2 COATINGS

A survey was made to determine the types of materials to be used in the coating. Most often, these materials were chosen on the basis of their unique electrical characteristics. If the electrical properties of the material were not of prime concern, materials were chosen for their ease of processing or availability.

3.2.1 Metal Foil Coatings

Alloy 1100, which is a minimum of 99.0 percent aluminum was used for all aluminum foils tested. This alloy has a density of 0.098 lb/in^3 or 1.4 lbs/100 square feet of 1-mil foil. Its electrical resistance is 2.92 micro-ohm-cm. The material obtained from The Boeing Company production stores was manufactured by the Alcoa Company. Very thin (0.0005 inch) material was obtained from Matheson, Coleman and Bell Company.

Reagent grade copper foils were purchased from Matheson, Coleman and Bell Company. This type of copper has an electrical resistance of 1.71 micro-ohm-cm. This corresponds to 101 percent of the volume resistivity of the International Annealed Copper Standard (IACS) at 20°C. The density of these copper foils is 4.65 lb/100 square feet of 1-mil foil.

High purity nickel foils were obtained from the Clevite Corporation, Cleveland, Ohio. Nickel has a density of 4.62 lb/100 ft^2 mil and an electrical resistivity of 11.0 micro-ohm-cm.

These materials were bonded to the test panels by one of the following methods:

A. 3M Company Scotch Grip Spray Adhesive 77, a rubber based material available in aerosol cans.

B. BMS 5-29J, an epoxy polyamide adhesive formulated from equal parts of Shell EPON 815 and EPON 828 with equal parts of General Mills Versamid 115 and Versamid 125. The adhesive is cured under vacuum at room temperature for at least 12 hours and post-cured for 1 hour at 175°F.

C. Integral bonding during laminate cure. In this case, the foil was in direct contact with the laminate during cure and the composite matrix served as the adhesive.

The latter technique yielded the most satisfactory results and provided a nearly void free bond line. Method (B) was subject to variations in bond line thickness and void content. Method (A) is the least satisfactory from a structural viewpoint; the rubber adhesive does not provide sufficient strength to prevent peeling of the aluminum foil at the panel edges.

The metal foils were prepared for bonding by wiping the surface with methyl ethyl ketone (MEK). Previously cured laminates were prepared for bonding by scouring with Scotch Brite, followed by a solvent wipe with MEK. Unless otherwise stated, the metal foils were bonded to the scrim cloth side of the boron fiber reinforced laminates.

Adhesive backed 1-inch wide, 3-mil thick aluminum tape was bonded to many composite panels. This electrical tape is 3M Scotch Brand Tape No. X-1170. The adhesive is pressure sensitive and is pigmented with a very small quantity of bronze colored pigment. The pigment provides electrical conductivity between the metal tape and the substrate. This tape was used for nearly all of the test panels which incorporated "expendable" metal strips into the coating system.

3.2.2 Metal Fabrics and Mesh

Woven wire cloth was purchased from Pacific Wire Products Company, Seattle. Several different material configurations were utilized. These are summarized in Table I. As a point of reference, the mesh count is defined as the number of openings or fractions thereof in a lineal inch; the fill wires are wires running the short way of the cloth as woven and the warp wires are the wires running the long way of the cloth as woven. A plain weave is one in which each warp (fill) wire passes over a fill (warp) wire, then under one, etc. A twilled weave is illustrated in Figure 1a. In this weave, each weave, each warp (filled) wire passes over two fill (warp) wires, then under two, etc.

The woven wire fabrics and knitted wire mesh were bonded to the composite panels with the BMS 5-29J or by the integral bonding techniques previously described with one exception--the silver plated brass mesh.

Table I: WIRE FABRIC MATERIALS

Metal Alloy	Mesh Density	Weave	Wire Dia. (in.)	Weight Lb/100 ft^2
Aluminum - 5056	60 x 60	Twilled	0.008	8.4
Aluminum - 5056	120 x 120	"	0.003	2.4
Aluminum - 1100	120 x 120	"	0.003	2.4
Aluminum - 5056	200 x 200	"	0.0021	1.9
Phosphor Bronze	100 x 100	Plain	0.0045	14.7
Phosphor Bronze	200 x 200	"	0.0021	6.4
Copper, Pure	100 x 100	Plain	0.0045	16.0
Stainless Steel (18-8)	325 x 325	Twilled	0.0014	4.1

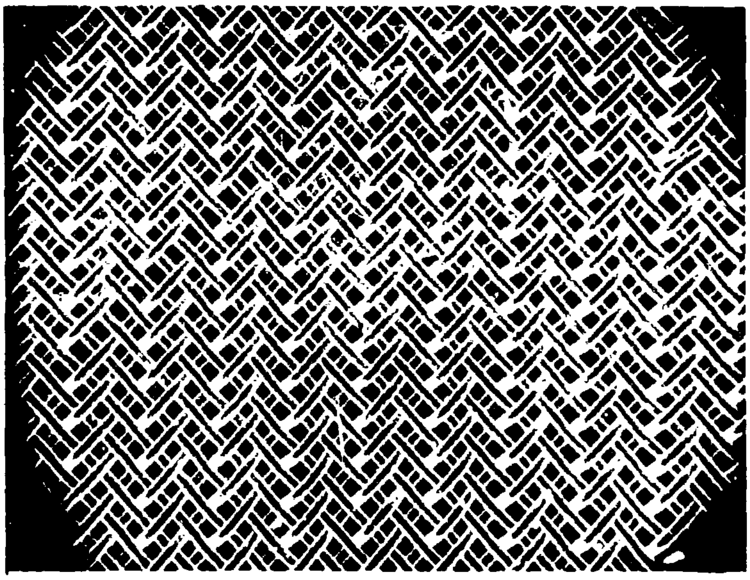
The brass wire meets MIL-SPEC-QQ-W-321B; however, the silver plating of the brass does not meet any Federal or Military specifications because these specifications are based on plating of flat surfaces. The brass wire has a 3 percent silver plating by weight. This mesh was bonded to the fiber reinforced panels with BMS 5-10, a room temperature curing epoxy adhesive tape. The wire mesh was partially embedded in the epoxy matrix and cured for 24 hours at room temperature under a 14 lb/in^2 confining pressure. The panels were post cured for two hours at 150°F. The boron panel utilized the adhesive tape as an overcoat, the graphite panel as an undercoat.

The copper utilized for macroscopic screen construction was 0.0021 inch diameter ordinary magnet wire. The wires were bonded to the panel surfaces with a small bead of BMS 5-29 adhesive.

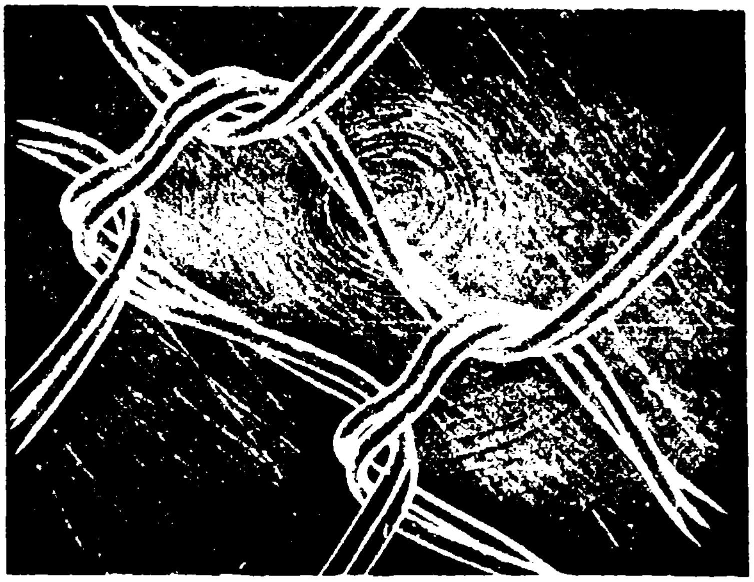
Knitted wire mesh was obtained from the Metex Corporation, Edison, New Jersey. Several different constructions were employed. These are summarized in Table II. A view of a knitted fabric is shown in Figure 1b. The difference in the construction of knitted and woven fabrics is apparent in the figure.

3.2.3 Plasma and Flame Spray

Plasma sprayed aluminum was applied to the panels using a nitrogen atmosphere to prevent oxidation. A thickness of 4-mils of flame sprayed aluminum was applied to a polyvinyl alcohol-polycinyl acetate (PVA) release film. Dow Chemical "MAPP" gas was used as the carrier. The panels were integrally bonded to the aluminum during cure. Release from the PVA film was affected by hot water. The boron panels released well, but some stripping of the coating from the boron-epoxy occurred. The graphite panels could not be released intact. These panels separated between



(a) 2.1-MIL WIRE, 200 X 200 MESH



(b) DOUBLE STRANDED 4-MIL WIRE, 13 X 24 MESH

Figure 1 ELECTRON SCANNING MICROSCOPE VIEWS OF WIRE FABRIC MATERIALS

Table II: KNITTED WIRE MESH

Metal	Wire Dia. (in.)	Mesh	Weight lb/100 ft^2
Aluminum	.003	13 x 24	0.48
	.003	10 x 18	0.36
	.004*	13 x 24	1.70
	.004	13 x 24	0.85
	.004	8 x 14	0.50
	.004	5 x 9	0.32
	.006	8 x 14	0.90
	.006	6 x 11	0.88
	.008	5 x 9	1.30
	.010	5 x 9	2.00
Monel	.002	22 x 40	2.60
Silver Plated Brass	.0035	13 x 24	2.20

*This knit used a double stranded 4 mil diameter aluminum wire

layers of graphite rather than at the release film. Presumably, this was due to the low interlaminar shear of the graphite composite and/or to resin bleed through which could form a permanent bond between the aluminum caul plate and the flame sprayed surface.

3.2.4 Pigmented Paints

3.2.4.1 Amine-Cured Epoxies

The coating base was prepared from EPON 1001, an epichlorohydrin/bisphenol A-Type epoxy resin. The curative, C-111, is a diethylene triamine adduct of EPON 1001 in a solvent solution. The resin and curative were mixed in the proportions recommended by Shell Chemical Company, and included 5 percent by weight of a flow control agent (Beetle 216-8, American Cyanamide Corporation). In unpigmented form, this coating vehicle served as a sprayable underlayer.

Pigmented paint was prepared by adding the desired amount of pigment to a solution which was 37.5 percent EPON 1001, 2 percent Beetle 216-8 and 60.5 percent solvent mixture by weight. The solvent had equal volumes of cellosolve acetate, methyl ethyl ketone and xylene.

The following materials were employed as pigments:

A. Boron Nitride (BN), Analyzed Reagent Grade Crystals, Alfa Inorganics Company.

B. Potassium Nitrate (KNO_3), Analyzed Reagent Grade Crystals, Matheson, Coleman and Bell Company.

C. Potassium Sulfate (K_2SO_4), Analyzed Reagent Grade Crystals, Matheson, Coleman and Bell Company.

D. Magnesium Nitrate ($Mg(NO_3)_2 \cdot 6H_2O$), Analyzed Reagent Grade Crystals, Matheson, Coleman and Bell Company.

E. Carbon Black, Cabot Vulcan XC-72, Grade Black.

F. Copper, 1 Micron Powder, Alfa Inorganics.

G. Aluminum, 325-Mesh Powder, Alfa Inorganics.

H. Sodium Nitrite ($NaNO_2$), Analyzed Reagent Grade Crystals, J.T. Baker Chemical Company.

The pigments were dispersed in the mixture using either a pebble mill or a ball mill; grinding or dispersion was accomplished in 4 to 24 hours. Upon completion of grinding, the pigmented vehicle was stored in a sealed metal paint container at 0°F. When needed, the paint was warmed to room temperature and the appropriate amount of catalyst was added; further dilutions with solvent mixture were made for spray application purposes. After coating, the paints were cured in a forced air oven for 1 hour at 150°F.

Several phenomena were observed during the processing of these coatings:

A. Uncatalyzed inorganic salt pigmented EPON 1001 gelled upon prolonged (>2 weeks) room temperature storage.

B. The magnesium nitrate system repeatedly precipitated from solution upon addition of the catalyst. As spraying was impossible, the coating was applied by brushing.

C. A 6 percent pigment volume concentration (PVC) is the maximum possible for this resin system when pigmented with Cabot XC-72 Black.

D. An attempt to prepare a sodium nitrite pigmented system was unsuccessful. The salt would neither dissolve nor disperse in the resin solution.

With the exception of the boron nitride pigmented system, which was not primed, all surfaces were primed with BMS 10-11, Type I, general purpose epoxy primer (Finch Base 463-6-3, converter X-306 and a thinner). The use of a primer was mandatory to assure good adhesion of the sprayable coatings to the Kapton film or to the epoxy matrix of the composite.

3.2.4.2 Thermoplastic Epoxies

The coating vehicle was Ciba Araldite 488E32, a thermoplastic epoxy. Pigments included:

A. Sterling MTNS black, a moderately conductive carbon.

B. Boron Nitride, Analyzed Reagent Grade Crystals, Alfa Inorganics Company.

C. Aluminum trifluoride (Al_2F_6), Research Organics/Inorganics.

D. 325-Mesh Aluminum Powder, Alfa Inorganics Company.

E. Lithium Chloride (LiCl) Powder, Research Organics/Inorganics.

The paints were prepared and applied as described previously. Some paints contained two pigments; in this case, one of the pigments was the MTNS black. The lithium chloride coating was prepared by sprinkling Research Organics/Inorganics lithium chloride powder over a wet Araldite-carbon black layer.

3.2.4.3 Silicones

Dow Corning 92-009 silicone was utilized as a vehicle for systems incorporating:

A. Al_2F_6, Research Organics/Inorganics.

B. Aluminum 325-mesh powder, Alfa Inorganics.

C. Copper purified powder, Matheson, Coleman and Bell Company.

These were prepared as above with the exception that no leveling agent was added to the vehicle. Dow Corning 1201 Silicone Primer was utilized for these systems.

3.2.4.4 Urethanes

Polyurethane based paints utilizing Finch clear base 683-3-2 and X-310 catalyst. The pigments were: Aluminum, Alcoa No. 552; and a "Gold" pigment, Product No. DG-10990, Claremont Polychemical Company (approximately 80-85 percent copper, 10-15 percent zinc, 2 percent silicone).

The paints were prepared by standard techniques and applied over an epoxy primer (BMS 10-11, Type 1). A final topcoat of 1 mil clear base 683-3-2 was also applied. The coatings were baked for 1 hour at 160°F.

3.2.5 Sandwich Coatings

Two metal sandwich coating systems were prepared. These three-coat sandwiches consisted of:

A. A thin clear base coat.
B. A solvent slurry of aluminum or copper.
C. A clear topcoat.

The metals were:

A. 325-mesh aluminum powder, Alfa Inorganics.
B. Purified copper powder, Matheson, Coleman and Bell Company.

The base coat, Shell Chemical Formulation No. CA-27-H-1 was applied to the panels and immediately a slurry of the metallic powder was sprayed onto the part. This slurry consists of 12 percent by weight pigment and 88 percent by weight solvent (a blend of 4 parts toluene to 1 part methyl isobutyl ketone).

Following application of the metallic slurry, the part is flash dried for 15 minutes at room temperature and then force dried for 30 minutes at 140°F. Top coat formulation CA-27-H-2 is then spray applied, flash dried 10 minutes at room temperature and given a final force dry of 90 minutes at 140°F.

3.2.6 Other Paint Systems

The silver-epoxy paint was EPO-TEK 401, supplied by EPOXY Technology, Inc., Watertown, Massachusetts. This paint was used without a primer and exhibited excellent adhesion to the substrates as applied by spraying. The panels were cured for 1 hour at 250°F. This paint has a volume resistivity less than 0.001 ohm-cm.

The copper paint was supplied by the Ablestik Adhesive Company, Gardena, California, under the trade name Abelbond 163-4. This copper filled epoxy paste was trowelled onto the panels to a finished thickness of 10-14-mils. The filler content was 82 percent by weight of 99 percent pure copper powder. The resistivity was approximately 0.005 ohm-cm.

The silver conductive coating was XC-4001 (Hanna Chemical Coatings Company, Columbus, Ohio), a silver pigmented thermoplastic system. The coating was applied by standard spray techniques. The reported conductivity is 90 micro-ohm-cm. BMS 10-11-Type 1, primer was used for this coating.

Dynacryl DA-B704, an aluminum pigmented all-purpose vinyl acrylic paint is manufactured by the Atlas Chemical Company, Miami, Florida. This paint was applied by spraying over a primer coat of BMS 10-11, Type 1. The paint was flash dried for 30 minutes at room temperature and force dried 30 minutes at 140°F.

3.2.7 Miscellaneous Coating Materials

"Kapton", a polyimide film manufactured by the E.I. duPont deNemours and Company, was employed as dielectric layer in several coating systems. One, two and 3-mil thick films were used. The most common electrical properties of "Kapton" polyimide film are given in Table III. These are the values reported by the manufacturer as measured at 25°C and 50 percent relative humidity.

Table III: TYPICAL ELECTRICAL PROPERTIES OF "KAPTON"

Dielectric Strength

Thickness	Typical Value	Test Method
1-mil	7000 v/mil	ASTM
2-mil	5400 v/mil	D-149-61
3-mil	4600 v/mil	

Volume Resistivity

Thickness	Typical Value	Test Method
1-mil	1×10^{18} ohm-cm	ASTM
2-mil	8×10^{17} ohm-cm	D-257-61
3-mil	5×10^{17} ohm-cm	

Kapton was bonded to the composites by one of the three methods described for the bonding of metal foils. The film was prepared for bonding to the composite by a MEK wipe. Kapton surfaces were prepared for painting by scouring with Scotch-Brite.

"Pyralin", a conductive polyimide coated glass fabric of various resistivities, is also manufactured by duPont. This material utilizes either 112 or 116 E style glass carrier fabrics and a carbon black pigment. It was bonded directly to composites with the previously described BMS 5-29J adhesive system.

Epoxy dielectric underlayers were simply 1 ply of the previously described BMS 8-79, with a 181 E style glass fabric carrier. This material was bonded to previously cured composite panels in an autoclave. The cure cycle was 90 minutes at 250°F and 40 psi.

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SECTION IV

LIGHTNING PROTECTION TEST APPARATUS

Past studies have shown that the damage introduced by a natural lightning stroke is primarily composed of two parts; a high current component which produces mechanical and electromagnetic damage and a high coulomb component which causes thermal and electrical heating damage. The high current discharge is usually a crest current with a peak amplitude from 10 KA to 200 KA and a pulse duration approximately up to 50 microseconds. A high coulomb component is usually a long duration low amplitude current component having a few hundred milliseconds to a few seconds duration and from less than 100 amps up to a few thousand amps. An artificial lightning stroke for test purposes is therefore defined as a high current and a high coulomb component to simulate the damage producing effects of natural lightning. All aspects or properties of natural lightning cannot be simulated in the laboratory due to limited space and energy available as well as the lack of a complete understanding of a lightning stroke; however for the present study, the test discharge (as shown in Figure 2) was used and is believed to have the requisite characteristics. They are:

A. A high current component rising from zero to a crest value of 200,000 amperes in 10 microseconds and a pulse duration of 20 microseconds with ± 50 percent tolerance on time.

B. A MIL-A-9094C type "C" high coulomb transfer discharge with total charge transfer equal to or exceeding 200 coulombs in one second or more.

During the initial phase study of the development and formulation of coatings suitable for potential lightning protection of composite structures, a high current component rising from zero to a crest value of 100 kiloamperes in 10 microseconds and a pulse duration of 20 microseconds with ± 50 percent on time was used. The application of this moderately severe stroke not only screened coating candidates for further study but aided the development of protective coatings for areas requiring only secondary protection such as the Zone II or the Zone III areas of an airplane (4).

The laboratory test setup is shown in Figure 3. The test panel was clamped to an 18-inch by 18-inch phenolic panel which was bolted to the Faraday Cage and was electrically isolated from the cage except for the ground strap that was clamped to one end of the panel. This configuration assured that the discharge current passed through the maximum available coating surface of a test panel. A positively grounded power supply system was used, i.e., the discharge probe injected discharging electrons toward the test panel to simulate a more severe damage situation than that of a negatively grounded power supply. A 1/4 inch diameter tungsten probe was used to direct the discharge to the test panel and a 1/4 inch gap was maintained between the probe and the panel.

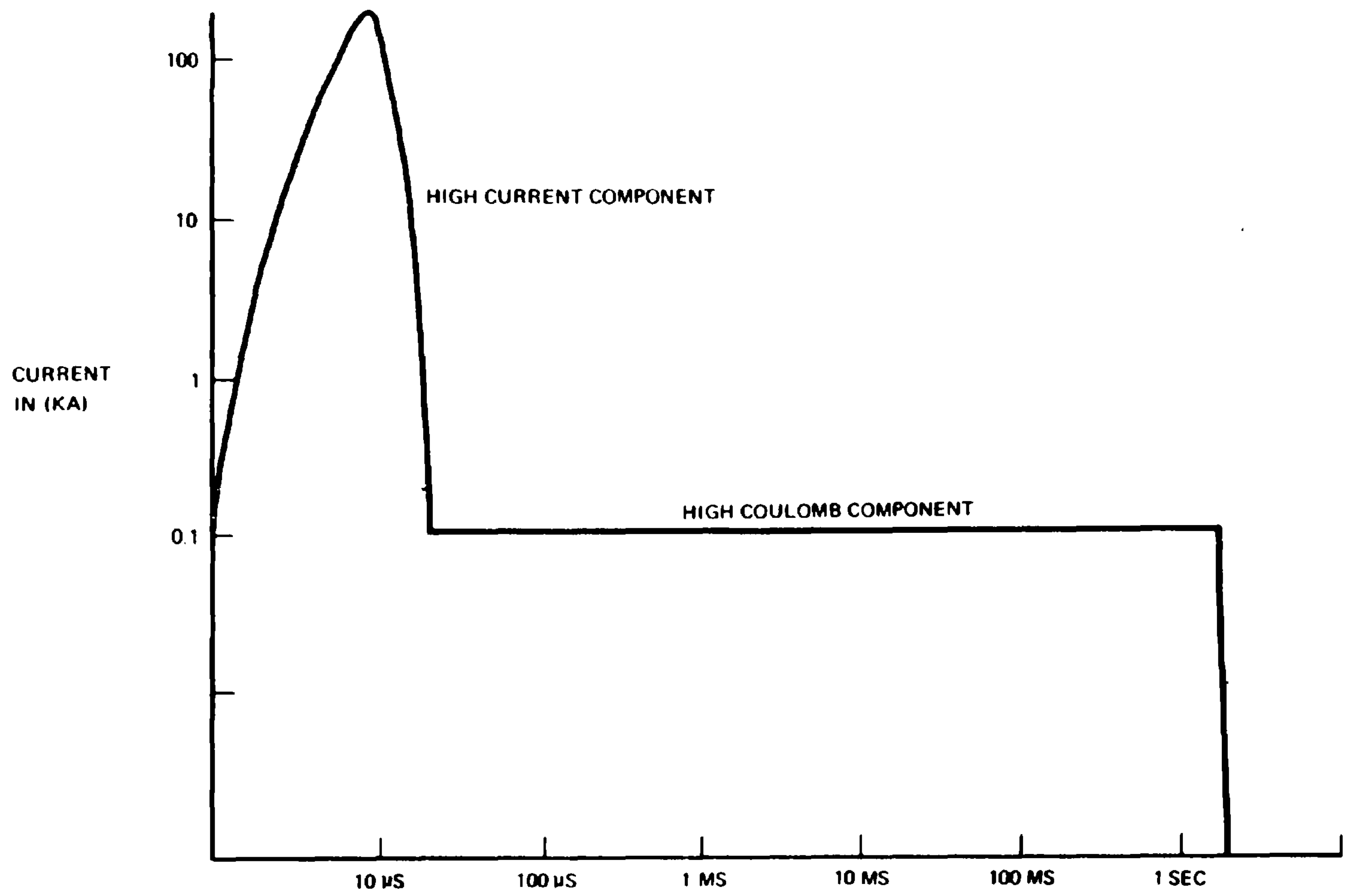


Figure 2: DISCHARGE CURRENT REQUIREMENTS

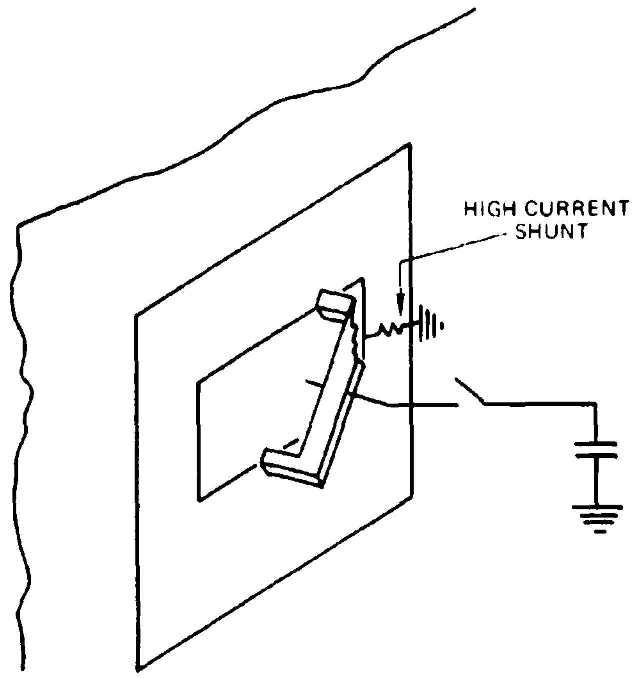


Figure 3: *LABORATORY TEST SETUP*

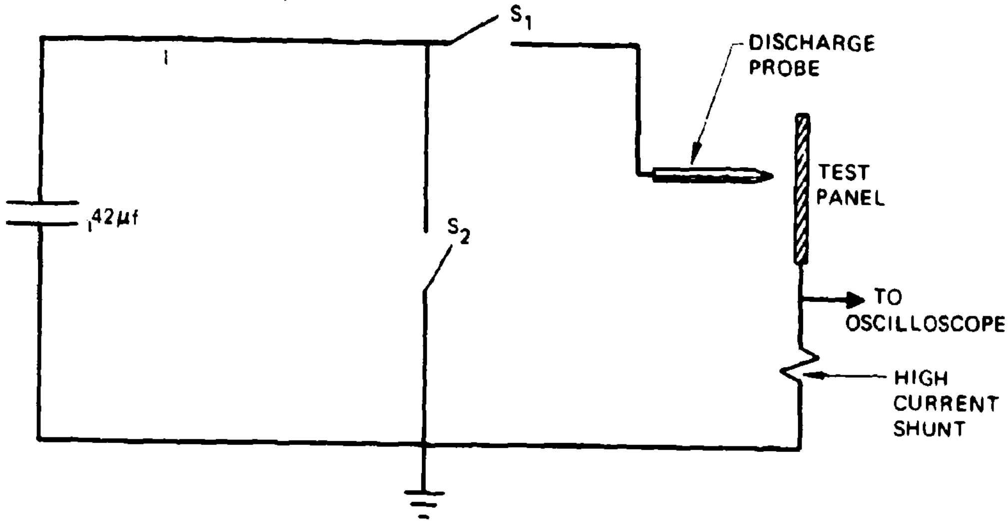
The Faraday Cage, a metallic box to provide electromagnetic shielding, was used not only to firmly hold the test panel during the discharge but also to house the equipment and test personnel for the induced voltage measurement task. The purpose of this task, was to measure the induced voltage in an individual fiber due to the high current component discharge. The test was accomplished by instrumenting a copper wire included in the laminate. The leads of the wire were connected to a load resistor in the Faraday Cage, and the output of the load resistor was connected to a Taktronix 422 battery powered oscilloscope. A polaroid camera, operated by an observer, was utilized to record the induced voltage.

To generate an artificial lightning strike in the lab, two different versions of the lab setup are used; the high current component generator as shown in Figure 4a and the two component generator as shown in Figure 4b. As illustrated in the schematic diagram of Figure 4a, a 42 microfarad capacitor bank rated at 30 KV is used to generate the high current component; the discharge was initiated by closing switch S_1. The discharging capacitor bank normally produces an underdamped oscillatory discharge due to the small damping ratio of the equivalent electrical circuit of the discharge path. The required single pulse discharge is produced by closing a crowbar switch S_2, as shown in Figure 4a, to shunt or crowbar the discharge currents parallel to the test panel immediately after the first half cycle oscillatory discharge.

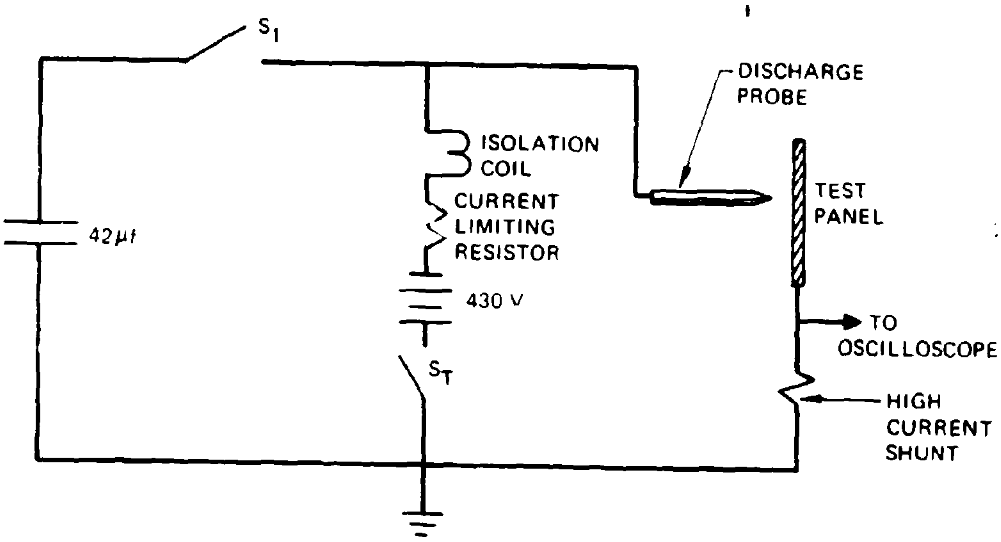
The crowbar switch S_2, a GE 37207 ignitron tube, is turned on by a high voltage pulse of 1200 volts at a predetermined time. The schematic diagram and the firing circuit of the crowbar switch are shown in Figure 5(a) and 5(b), respectively. As shown, the Hewlett Packard Model 214 Delay Pulse Generator will be triggered by the induced voltage of the initial capacitor discharge from the pickup loop. The isolation and step-up transformer will then deliver a 200 volt delayed pulse to the triggering terminal of a Krytron (KRP-21 by Edgertron, Germeshausen & Grier Co.). The triggered Krytron delivers a 1200 volt pulse to the ignitor of the ignitron tube as shown in Figure 5(b). Three typical crowbarring discharge waveforms are shown in Figure 6(b), (c) and (d). Theoretically, closing the crowbar switch will shunt the discharge current and stops all current flow through the test item; however, as illustrated by the oscillatory nature in Figure 6(a), current continued to flow through the test item after S_2 was activated. This is undoubtedly due to the finite impedance of the discharge path which continued to share current with the lower impedance of the parallel crowbar circuit. Nevertheless, this type of discharge adequately simulates lightning damage for the purposes of the study.

The discharge current was measured by a high current shunt of 60 micro-ohm impedance made by The Boeing Company. The output of this shunt was connected to a Tektronix 549 oscilloscope to record the discharge current.

A block diagram of a two component lightning generator is shown in Figure 4b. The high current component generator will first establish an

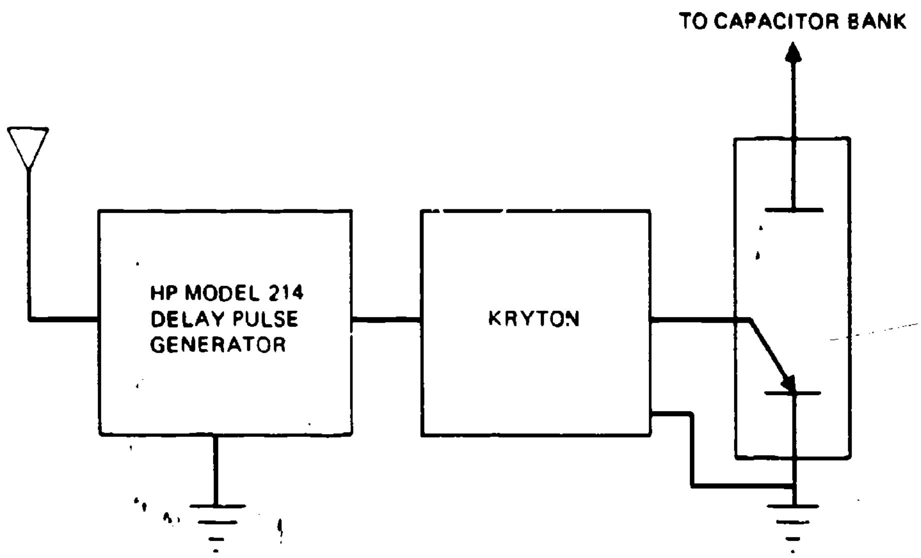


(a) HIGH CURRENT GENERATOR

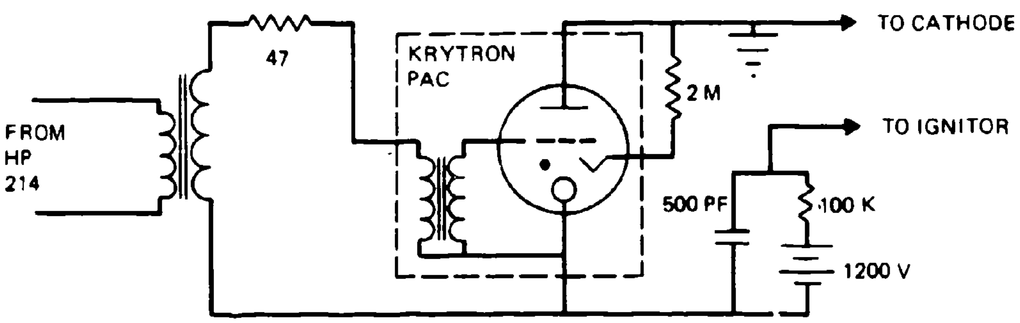


(b) TWO COMPONENT GENERATOR

Figure 4. LIGHTNING SIMULATOR

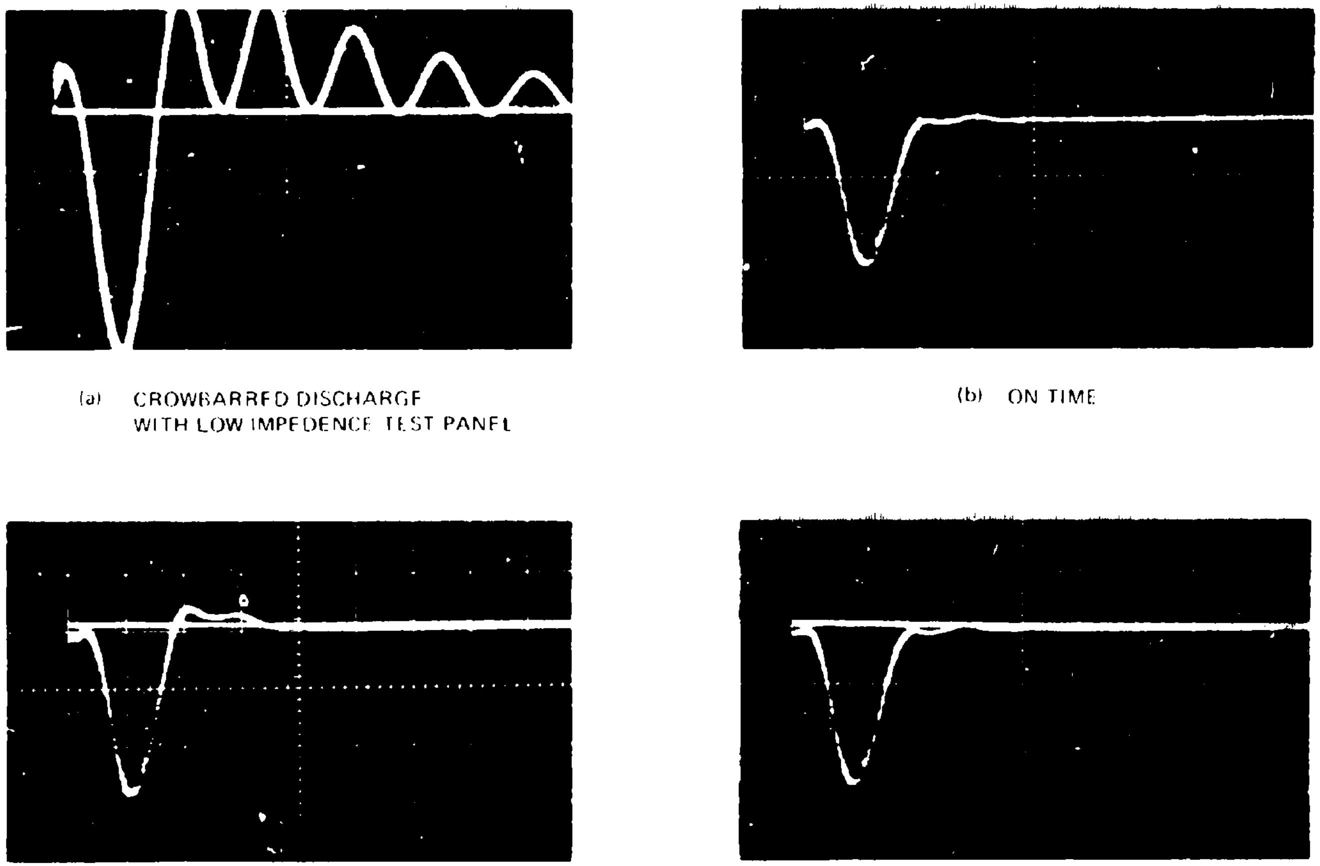


(a) BLOCK DIAGRAM OF CROWBAR SWITCH



(b) SCHEMATIC DIAGRAM OF KRYTRON CIRCUIT

Figure 5: CROWBAR SWITCH



(a) CROWBARRED DISCHARGE WITH LOW IMPEDENCE TEST PANEL

(b) ON TIME

(c) DELAYED

(d) EARLY

Figure 6. *TYPICAL CROWBARRED DISCHARGE CURRENT WAVEFORMS*

arc between the discharge probe and the test item and the high coulomb component generator will then follow-on by discharging a DC component through the established ionized channel to the test panel. The charged high voltage capacitor bank is electrically isolated from the battery bank by the switch S_1; these high current and high coulomb components are transiently isolated from each other by the isolation coil. The total discharge is terminated by opening the switch S_T.

An oscillatory, instead of the previously discussed crowbarring, capacitor bank system is employed with the same 42 microfarad capacitor bank. This is necessary because the high coulomb component currents from the battery bank will otherwise flow through both the crowbar switch and the discharge path; the excessive DC current which flows through the crowbar switch will not only degrade the available testing energy but will also greatly reduce the lifetime or damage the ignitron tube. The extra coulomb value provided by the additional discharge from the capacitor blank is less than 1 percent of the total amount of the two component stroke.

Two 430 volt battery carts are utilized for the required high coulomb component. Each steel cart with the dimensions of 73 inches by 49 inches and 50 inches high has been configured with 36 12-volt automotive batteries and has a total weight of about 2200 pounds. With different series or parallel connections the system is capable of discharging a DC level up to 3000 amperes and maintaining an arc with a gap of up to a half-inch.

The schematic diagram of the timing switch S_T (Figure 4b) which provides a cutoff time for the battery bank of up to 5 seconds is shown in Figure 7. A flash from the initial capacitor bank discharge will turn on D_1, a light activated silicon controlled rectifier (LASCR), in less than 6 microseconds. Once the LASCR is on, the 28.35 volt power supply will be latched to Q_2, a field effect transistor, which works as a constant current source, therefore, the capacitor C will be charged linearly. When the capacitor is charged to 12 volts, Q_4, an unijunction transistor, will be turned on to activate L_2 to change S_2 to position 2; then L_1 will be de-activated to change S_1 to position 2. By this procedure the battery cart will be disconnected from the lightning discharge path. Q_3 works as a source follower to increase the linearity of the charging rates of the capacitor. The timing of the whole device is controlled by the 3 kilo-ohm potentiometer which limits the amount of current from the current source. Three 9.45 volt mercury cells are used for the 28.35 and 18.9 volts power supply. A 90 volt dry battery is used to power L_1. A GE 1C2800-Y102A-3, a normally open circuit breaker, is used in the timing switch.

Referring to the schematic diagram of an artificial lightning stroke simulator as shown in Figure 4b, the discharge path of the battery bank can be represented by the schematic diagram of Figure 8.

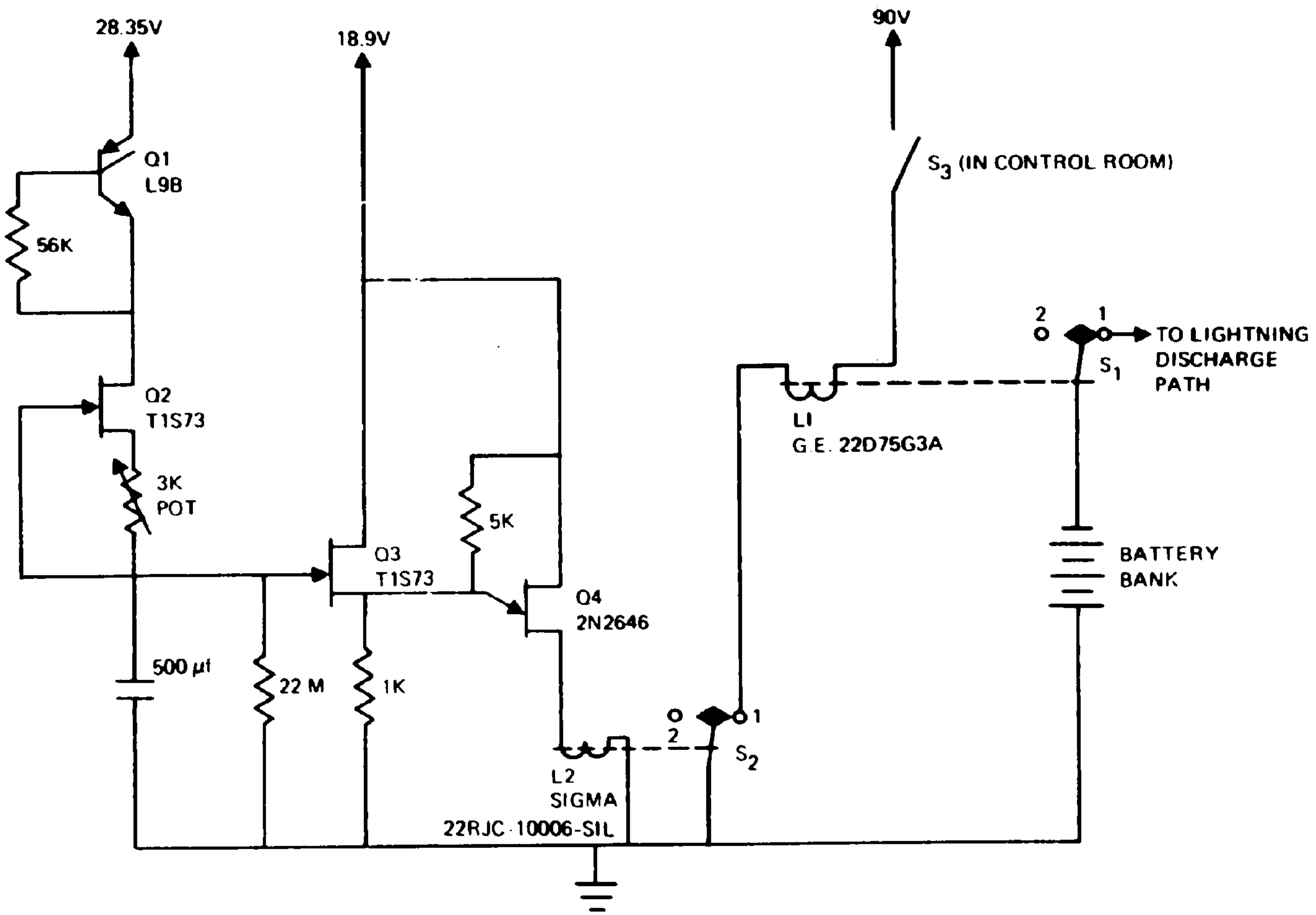


Figure 7. SCHEMATIC DIAGRAM OF THE TIMING SWITCH

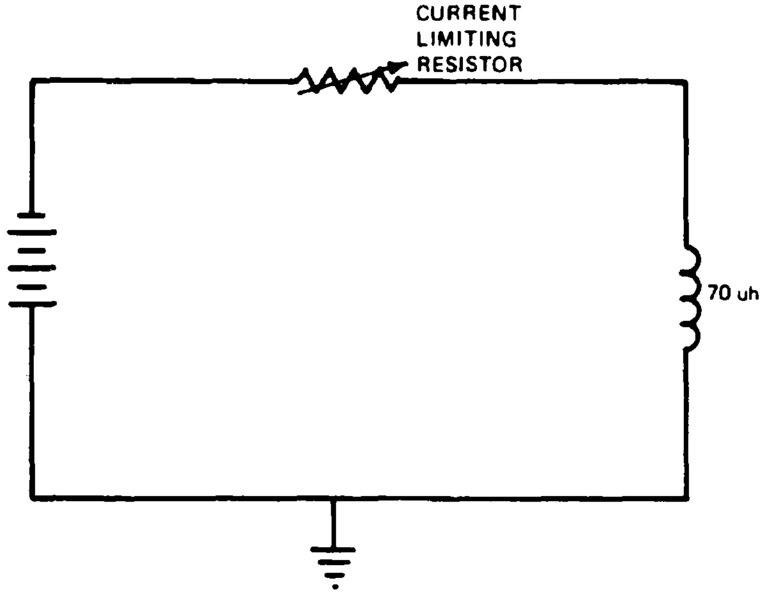


Figure 8: *EQUIVALENT CIRCUIT OF LIGHTNING GENERATOR*

A circuit analysis yields the following equation for this circuit:

$$I(t) = \frac{V}{R}\left(1 - e^{-\frac{R}{L}t}\right) \tag{1}$$

For a typical operation, i.e., a 250 amp discharge, the rise time will be:

t = 4.1 us for 10% of current rise, or 25 amp
t = 26.9 us for 50% of current rise, or 125 amp
t - 89.3 us for 90% of current rise, or 225 amp

Since the discharge of the battery bank depends on the existence of a conductive channel which is established by the discharge of a capacitor bank, a time coordination must exist between the capacitor and battery banks. The exact timing between these two banks cannot be defined theoretically because of the lack of a full knowledge about the characteristics of the discharge arc. However, theoretical calculations show the central temperature in the ionized channel of a lightning stroke will usually drop to 7000°C or 8000°C within 1 millisecond of the cessation of a lightning discharge (5). At this temperature, the electrical conductivity of the air is between 3.90 mhos/cm and 10.4 mhos/cm (6). These arguments combined with the rise time calculations of the battery bank, indicate the battery bank should be able to "follow-on" with no difficulties. Laboratory tests show this is true, but the batteries cannot be discharged if the gap between the probe and the test panel is greater than 1/2 inch.

SECTION V

TEST RESULTS AND DISCUSSIONS

A numbering system has been devised for test panel identification and description. It consists of the following sixteen digits:

XXX	XX	XX	XX	XX	X	XX	XX
Test Serial Number	Type of Panel	Serial Number of Panel	Type of Coating	Thickness of Coating	Coating Coverage	Type of Under-Coating	Thickness of Under-coating

The numbering system has the following significance:

Test Serial Number:	A three digit number unique to each panel.
Type of Panel:	Two letters describing the composite reinforcement, e.g., BR=boron filament, GP=graphite fiber, FG=181E style glass fabric and AL=aluminum.
Serial Number of Panel:	A two digit number unique to the particular reinforcement.
Type of Coating:	A two letter code describing the coating, e.g. AF is the designation for aluminum foil.
Thickness of Coating:	In mils and including primer.
Coating Coverage:	A one letter code describing the degree of surface coverage, mesh density of a fabric coating, or attached with diverter strips.
Undercoating:	A two letter code defining the undercoat system, e.g., KF=Kapton film.
Thickness of Undercoat:	In mils

For example, a designation of 023-GP05-AF03C-KF02 stands for the twenty-third test, the fifth graphite panel tested, a 3-mil protective coating of aluminum foil providing complete coverage of the panel surface, and a 2-mil undercoating of Kapton film; a designation of 232-BR97-AD08G-0000 stands for the two hundred and thirty-second test, the ninety-seventh boron panel tested, a 4-mil wire diameter aluminum knitted wire mesh with a mesh density of 10 x 18 as the coating, but no undercoating was applied. All abbreviations for the numbering system are listed in Table IV.

Table IV: ABBREVIATIONS FOR PANEL DESIGNATION

A = 6 x 11 mesh

AD = knitted aluminum wire mesh

AE = epoxy paint filled with aluminum

AF = aluminum foil

AK = silicone paint filled with aluminum

ALCO = aluminum honeycomb core

AM = knitted monel wire mesh

AP = plasma-sprayed aluminum

AR = woven aluminum wire fabric

AS = flame-sprayed aluminum

AU = polyurethane paint filled with aluminum

B = 5 x 9 mesh

BN = boron nitride filled epoxy

BR = boron filament reinforced composite

C = completely coated

CC = carbon cloth

CE = epoxy paint filled with copper

CF = copper foil

CK = silicone paint filled with copper

CM = epoxy paint filled with micron size copper powder

CR = woven copper wire fabric

CU = polyurethane paint filled with copper

CW = copper wire

DE = epoxy paint filled with potassium nitrate

E = 13 x 24 mesh per inch

EP = epoxy paint

F = 8 x 14 mesh

FE = woven stainless wire fabric

FG = glass fabric reinforced composite

G = 10 x 18 mesh

GP = graphite fiber reinforced composite

H = 22 x 40 mesh

J = 13 x 24 mesh with double stranded wire

KF = Kapton film

LK = silicone paint filled with aluminum trifluoride

ME = epoxy paint filled with MTNS carbon black

NI = nickel foil

P = partially coated

PE = epoxy paint filled with potassium sulfate

QE = epoxy paint filled with aluminum and carbon black

SA = silver pigmented acrylic paint

Table IV: ABBREVIATIONS FOR PANEL DESIGNATION (CONT.)

SE	=	epoxy paint filled with silver
SG	=	glass fabric impregnated with silver filled epoxy paint
SW	=	silver plated brass wire
T	=	expendable aluminum diverter strips
U	=	100 x 100 mesh
UE	=	epoxy paint filled with XC-72, conductive black
VA	=	vinyl acrylic paint
W	=	60 x 60 mesh
X	=	120 x 120 mesh
XE	=	epoxy paint filled with carbon black and overcoated with lithium chloride
Y	=	325 x 325 mesh
YE	=	epoxy paint filled with aluminum trifluoride and carbon black
Z	=	200 x 200 mesh

5.1 SCREENING TEST RESULTS

A total of 261 coated and uncoated panels were tested during the screening test effort of this study. Data from these panels have been summarized in Table V, and a detailed description of every test panel is reported in the Appendix. The test results and their significance are discussed in Section 5.1.1 and following.

5.1.1 Uncoated Panels

Uncoated panels were tested in two configurations. One configuration utilized a standard panel with the two outer plies and the middle plies electrically grounded. The other configuration was the same except that the test panel contained a 1-mil film of Kapton integrally bonded between the two fiber plies nearest the discharge probe.

Due to the higher impedance of the boron substrate compared to a metallic coating, the discharge current level was reduced to less than a half of its normal level, i.e., a recorded 43 KA discharge resulted from an uncoated boron panel test while the simulator was originally set to have a 100 KA discharge. At this discharge level, both boron test panels received a series of holes along the 6-inch direction at the discharge zone. Severe delamination was also observed on the back side. Fiber-resin bonding was destroyed by the high current and is shown by the mottled appearance of both panels. Kapton film did little to prevent damage and seemed to localize the damage along the 6-inch panel direction. This is illustrated in Figure 9, Panel 039 and 040.

An uncoated boron fiber reinforced panel was completely destroyed by a 175 KA discharge as shown in Figure 10. The panel was shattered into many pieces, the largest of which is approximately 3 inches by 6 inches. The retrievable pieces of the panel amount to approximately 60 percent of the original five ply, 6 x 12 inch test piece. These results show that damage to boron fiber reinforced composites of this thickness can be affected by panel size. The small, 72 square inch panels do not allow complete energy dissipation. Thus, lightning damage to larger structure may encompass much larger areas than that confined within these boron test specimens.

The graphite panels displayed less damage than boron for equivalent discharges. The panel without the Kapton film was delaminated on the front side and evidence of current introduction into subsequent plies was clearly visible. Damage radiated both toward and away from the electrical ground connection at the base of the panel. The panel containing the inner layer of Kapton sustained no back side damage and no explosive delamination of the outer ply. Current obviously penetrated the Kapton to the second ply as shown by the delamination and burning along the 6-inch direction. Current conduction by the outer plies left the panel surface rippled. These effects are also illustrated in Figure 9.

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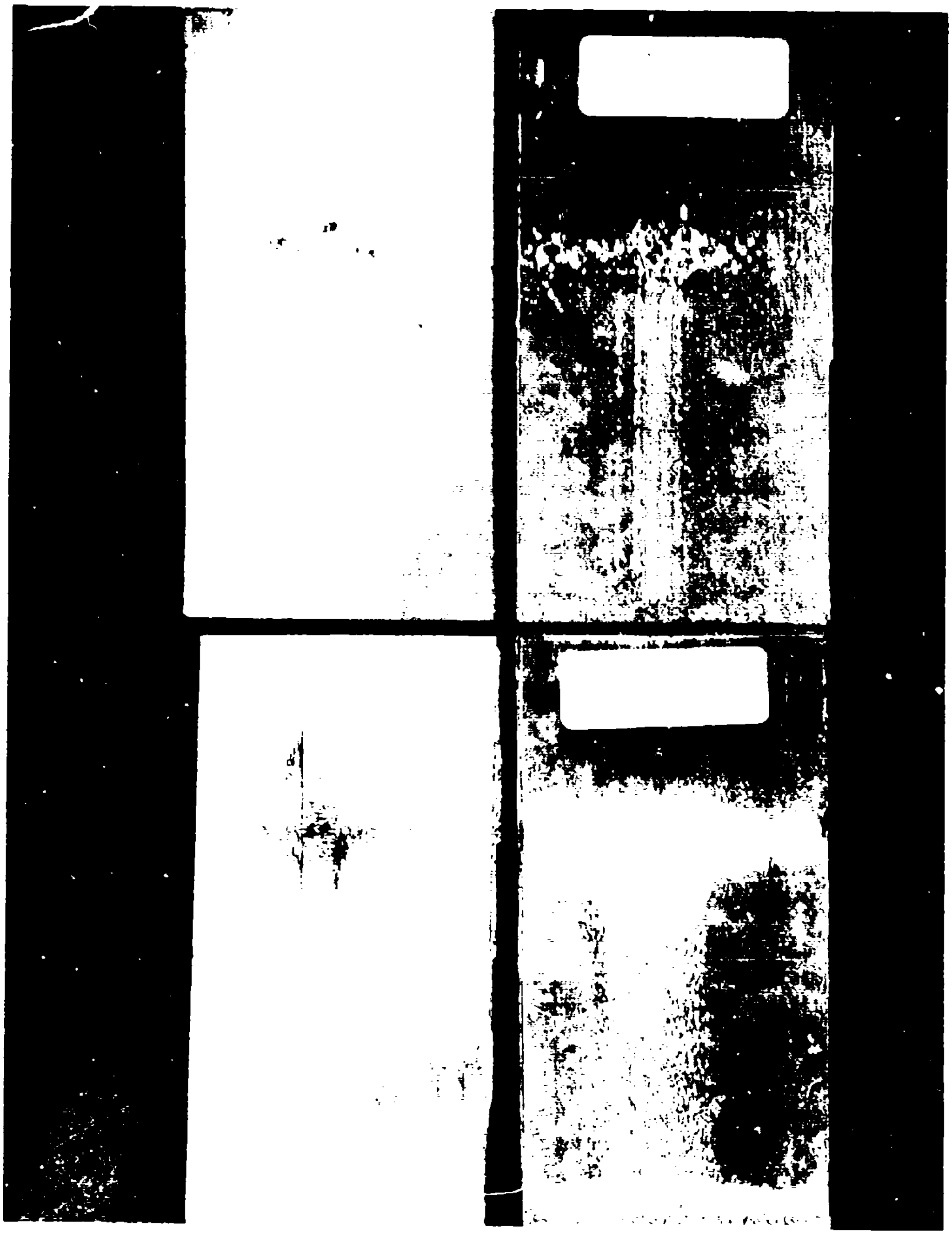


Figure 9 LIGHTNING DAMAGE TO UNCOATED BORON EPOXY AND GRAPHITE EPOXY LAMINATES

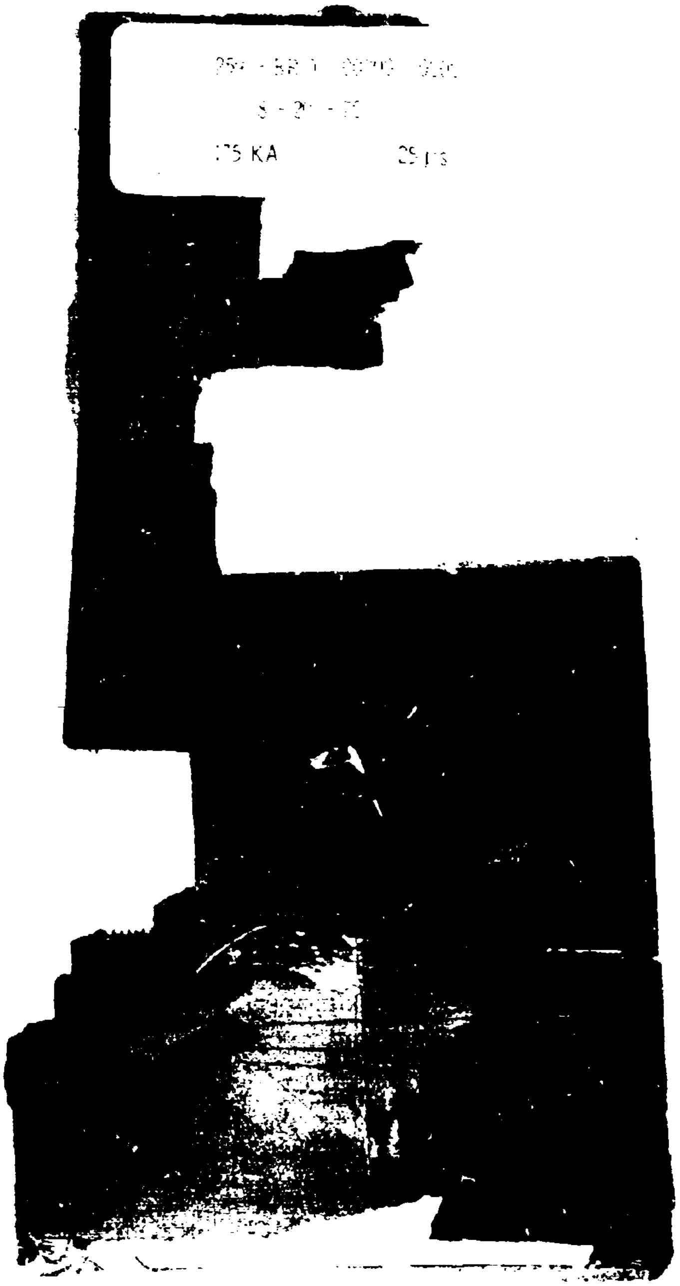


Figure 10. 175 KA SIMULATED LIGHTNING DAMAGE TO BORON EPOXY LAMINATE

Table V: SUMMARY OF SCREENING TEST RESULTS

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
001-FG01-AF02C-0000	80	40	1. No visible damage.
002-FG02-AF03C-0000	80	40	1. No visible damage.
003-FG03-AF03C-0000	80	40	1. No visible damage.
004-FG04-AF02C-0000	90	40	1. No visible damage.
006-FG06-AF01C-0000	110	25	1. No visible damage.
007-FG07-AF01C-0000	110	25	1. No visible damage.
008-FG08-AF01C-KF01	110	25	1. No visible damage.
009-FG09-AF01C-KF01	110	25	1. No visible damage.
010-FG10-AF01C-KF02	110	25	1. No visible damage.
011-FG11-AF01C-KF02	110	25	1. No visible damage.
012-FG12-AF01C-KF03	110	25	1. No visible damage.
013-FG13-AF01C-KF03	110	25	1. No visible damage.
014-FG14-AF01P-0000	110	25	1. No visible damage.
015-FG15-AF01P-0000	110	25	1. No visible damage.
016-BR01-AF01C-KF01	87	30	1. No visible damage.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
017-BR02-AF01C-0000	100	32	1. No visible damage to the substrate.
018-BR03-AF01P-0000	94	32	1. No visible damage to the substrate. 2. Vaporized Al strips.
019-GP01-AF01C-0000	94	32	1. No visible damage to the substrate.
	167	Oscillatory	1. Very severe damage to the substrate.
020-GP02-AF01P-0000	94	32	1. No visible damage to the substrate.
021-GP03-AF03C-0000	94	32	1. Damage to the substrate.
022-GP04-AF03C-KF01	94	30	1. No visible damage to the substrate. 2. Slight damage to the Kapton film undercoating.
023-GP05-AF03C-KF02	94	30	1. No visible damage to the substrate.
024-GP06-AF01C-KF01	94	30	1. No visible damage to the substrate.
025-GP07-AF01C-KF03	94	30	1. No damage to the substrate. 2. Small burned spot on Kapton film.
026-GP08-AF03C-KF03	123	30	1. Cracked substrate.
027-GP09-AF01C-KF02	100	30	1. No damage to the substrate. 2. Small burned spot at discharge c [illegible]er.
028-BR04-AF03C-KF03	100	30	1. No visible damage to the substrate.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
029-BR05-AS04C-0000	100	30	1. No damage to the substrate. 2. Burned marks on flame-sprayed aluminum surface.
030-BR06-AS04C-0000	100	30	1. No damage to the substrate. 2. Burned marks on flame-sprayed aluminum surface.
	160	Oscillatory	1. Very severe damage to the substrate.
031-BR07-AF03C-KF02	109	30	1. Cracked substrate.
032-BR08-AF03C-0000	107	30	1. Cracked substrate.
033-BR09-AF01C-KF03	107	26	1. No damage to the substrate.
034-FG16-AF02C-KF03	160	Oscillatory	1. No damage to the substrate.
035-FG17-AF02C-KF03	100	26	1. No damage to the substrate.
036-BR10-AF01C-0000	100	[illegible]	1. Cracked substrate. 2. Burned marks along edges.
037-BR11-AF01C-KF02	100	26	1. No damage to the substrate.
038-BR12-AF03C-KF01	100	26	1. No damage to the substrate.
039-BR13-00000-KF01	43	44	1. Several holes punctured the substrate. 2. Burned marks all over the front surface. 3. Few burn marks on the backside around the discharge center.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
040-BR14-00000-0000	43	44	1. Severe damage to the front surface. 2. Burned marks all over the front surface. 3. Few burn marks on the back side.
041-BR15-AF01C-0000	95	28	1. No damage to the surface of the panel. 2. Panel cracked along the direction of fibers (Fibers are unidirectional for this panel.)
042-BR16-AF01C-0000	95	28	1. Cracked substrate.
043-BR17-AF01C-0000	95	28	1. No damage to the substrate.
044-GP10-AF06C-0000	95	28	1. Small burned marks on the surface of the substrate.
045-BR18-AF01C-0000	95	28	1. No damage to the substrate.
046-BR19-AF06C-0000	95	28	1. No damage to the substrate.
047-GP11-AF06P-0000	95	28	1. Burned front surface. 2. Cracked substrate.
048-GP12-AF06P-0000	95	28	1. Burned front surface. 2. Cracked substrate.
049-BR20-AF06P-0000	95	28	1. No damage to the substrate.
050-BR21-AF06P-0000	95	28	1. No damage to the substrate.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
051-GP13-CE10C-0000	100	27	1. Severely burned front surface of the substrate.
052-FG18-SE05C-0000	90	30	1. No damage to the substrate. 2. Coating discolored.
053-GP14-SE03C-0000	92	26	1. Severely damaged coating. 2. Burned front surface of the substrate.
054-BR22-CU05C-0000	36	60	1. Very severely damaged substrate.
055-GP15-00000-0000	92	28	1. Very severely damaged substrate.
056-GP16-00000-KF01	89	29	1. Very severely damaged substrate.
057-FG19-AU05C-0000	90	30	1. No damage to the substrate.
058-BR23-CE10C-0000	81	32	1. Cracked substrate.
059-BR24-SE05T-0000	100	30	1. No damage to the substrate.
060-BR25-SE05C-0000	90	30	1. Cracked substrate. 2. Severely burned coating.
061-GP17-CU05C-0000	110	28	1. Very severely damaged substrate.
062-BR26-AU05C-0000	36	60	1. Very severely damaged substrate. 2. Bubbled coating surface.
063-GP18-AU05C-0000	103	28	1. Very severely damaged substrate.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
064-FG20-AF01C-EP02	105	26	1. No visible damage to the substrate. 2. Undercoating of epoxy paint was burned.
065-FG21-SE03C-CC07	70	31	1. No visible damage to the substrate. 2. Discolored silver paint.
066-FG22-CR09U-0000	98	26	1. No visible damage to the substrate.
067-FG23-CR09U-0000	98	26	1. No visible damage to the substrate.
068-GP19-AP05C-0000	94	26	1. Burned front surface of the substrate. 2. Burned plasma-sprayed aluminum surface.
069-FG24-AF04P-AU06	91	27	1. No damage to the substrate.
070-FG25-AU06C-CC07	95	27	1. No visible damage.
071-FG26-AF04P-CC07	105	27	1. No damage to the substrate.
072-BR27-AP06C-0000	105	25	1. Small crack on the back side of the substrate.
073-BR28-AP02C-0000	100	25	1. Small crack on the back side of the substrate. 2. Burned plasma-sprayed aluminum surface.
074-GP20-AP02C-0000	100	25	1. No damage to the substrate. 2. Burned plasma-sprayed aluminum surface.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
075-BR29-AF01C-ALCO	90	26	1. No visible damage.
076-GP21-AF01C-ALCO	90	26	1. No visible damage.
077-BR30-CR09U-0000	90	25	1. No visible damage.
078-GP22-CR09U-0000	90	25	1. No visible damage.
079-BR31-AU06C-KF01	50	40	1. Severely damaged substrate.
080-GP23-AU06C-KF01	85	28	1. Severely damaged substrate.
081-BR32-CR09U-0000	90	26	1. No visible damage.
082-GP24-CR09U-0000	90	26	1. No visible damage.
083-GP25-AU06C-CC07	70	28	1. Severely damaged substrate.
084-BR33-AU06C-CC07	60	28	1. Severely damaged substrate.
085-BR34-AF04P-AU06	90	28	1. Severely damaged substrate.
086-GP24-AF04P-AU06	90	26	1. Severely damaged substrate.
087-BR35-AF04P-CC07	88	27	1. Severely damaged substrate.
088-GP27-AF04P-CC07	90	28	1. Severely damaged substrate.
089-BR36-SE03C-CC05	81	27	1. Damaged substrate. 2. Carbon cloth peeled off. 3. Discolored silver paint.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
090-GP28-SE03C-CC07	81	27	1. Severely damaged substrate.
091-BR37-SE03C-0000	85	29	1. Damaged substrate. 2. Discolored silver paint.
092-BR38-SE03C-CC07	85	28	1. Damaged substrate. 2. Discolored silver paint.
093-GP29-AK05C-0000	90	29	1. Severely damaged substrate.
094-BR39-AK05C-0000	51	70	1. Severely damaged substrate.
095-FG27-AF03C-CC05	100	26	1. No visible damage to the fiberglass panel. 2. Carbon cloth undercoating was slightly burned.
096-BR40-CW02P-0000	114	Oscillatory	1. The substrate was broken. 2. Copper wires were vaporized.
097-FG28-CK07C-0000	114	Oscillatory	1. No visible damage to the fiberglass panel. 2. Discoloration of coating.
098-BR41-CK07C-0000	100	32	1. The substrate was broken. 2. Coating was discolored and burned.
099-BR42-CF02C-0000	95	Oscillatory	1. No visible damage to the substrate.
100-GP30-CW02P-0000	72	30	1. The substrate was broken.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
101-GP31-CF02C-0000	95	27	1. No visible damage.
102-GP32-AF03P-SE02	91	27	1. Burned substrate surface. 2. Back side of substrate was slightly cracked.
103-BR43-AF03P-SE03	100	27	1. The back side of substrate was slightly cracked and a mark of a possible collision of the discharge probe was shown on the front surface.
104-FG29-CM08C-0000	100	31	1. No visible damage to the fiberglass panel. 2. Discolored coating.
105-FG30-CR04Z-0000	95	27	1. No visible damage to the substrate.
106-GP33-CR04Z-0000	100	27	1. No visible damage to the substrate.
107-BR44-CR04Z-0000	98	27	1. No visible damage to the substrate.
108-GP34-CK07C-0000	89	28	1. Severely damaged substrate.
109-GP35-CM08C-0000	83	30	1. Severely damaged substrate.
110-BR45-CM08C-0000	43	58	1. Severely damaged substrate.
111-FG31-SG12C-0000	90	29	1. No visible damage to the fiberglas panel. 2. Coated cloth was badly burned.
112-FG32-AE05C-0000	90	29	1. No visible damage to the substrate.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
113-GP36-AE05C-0000	83	30	1. Severely damaged substrate.
114-BR46-AE05C-0000	83	31	1. Severely damaged substrate.
115-GP37-N101/2C-0000	100	28	1. The substrate was not punctured; however, the surface of the substrate was burned.
116-BR47-N101/2C-0000	100	28	1. No damage to the substrate was observed.
117-GP38-ME02C-0000	89	29	1. The substrate was severely damaged.
118-BR48-AR04Z-0000	111	26	1. No damage to the substrate was observed.
119-BR49-LK14C-0000	50	Oscillatory	1. The substrate was severely damaged.
120-GP39-LK14C-0000	87	32	1. The substrate was severely damaged.
121-GP40-SG12C-0000	97	28	1. No visible damage to the substrate was observed. 2. The coating was discolored and cracked.
122-BR50-SG12C-0000	9[illegible]	28	1. The back side of the substrate was slightly cracked; a mark of a possible collision from the discharge probe was evident on the front surface of the substrate. 2. The coating was discolored and cracked.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
123-FG33-AR04Z-0000	102	26	1. No damage to the control panel was observed.
124-GP41-AR04Z-0000	107	26	1. No damage to the substrate was observed.
125-BR51-ME02C-0000	39	52	1. The substrate was severely damaged. 2. The coating was melted and bubbled.
126-FG34-AE07C-0000	105	Oscillatory	1. No visible damage to the substrate was observed. 2. The coating was badly melted.
127-FG35-CE08C-0000	No	N/A	1. No damage to the control panel was observed. 2. The coating was burned and pitted.
128-BR52-CE09C-0000	72	52	1. The substrate was severely damaged. 2. The coating was badly melted.
129-GP42-CE11C-0000	122	Oscillatory	1. The substrate was severely damaged.
130-GP43-CE09C-KF03	122	Oscillatory	1. The substrate was not punctured but the edges of the substrate were split; however, the degree of damage to the substrate was less than that to Panel No. 129.
131-GP44-AE10C-0000	84	31	1. The substrate was very badly damaged.
132-BR53-AE12C-0000	48	54	1. The substrate was severely damaged. 2. The coating was badly melted.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
133-FG36-AR16W-0000	104	26	1. No damage to the panel was observed.
134-BR54-AR16W-0000	104	26	1. No damage to the substrate was observed.
135-GP45-AR16W-0000	105	26	1. No damage to the substrate was observed.
136-FG37-AR16P-0000	106	28	1. No damage to the substrate was observed. 2. The center strip was vaporized.
137-GP46-AR16P-0000	106	25	1. The front surface of the substrate was badly burned. 2. The center strip was vaporized.
138-BR55-AR16P-0000	106	27	1. No damage to the substrate was observed. 2. The center strip was vaporized.
139-GP47-QE07C-0000	97	29	1. The substrate was severely damaged.
140-GP48-QE06C-BN05	93	29	1. The substrate was severely damaged.
141-GP49-XE12C-0000	93	28	1. The substrate was severely damaged. 2. The front surface was moist.
142-GP50-YE09C-BN03	93	28	1. The substrate was severely damaged.
143-BR56-XE11C-0000	47.5	52	1. The substrate was severely damaged. 2. The coating was badly burned.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
144-BR57-QE07C-0000	82	32	1. The substrate was severely damaged. 2. The coating was burned off.
145-BR58-QE06C-BN05	75	35	1. The substrate was severely damaged and broken.
146-BR59-YE09C-BN03	42	52	1. The substrate was severely damaged. 2. The coating was severely deteriorated.
147-FG38-QE07C-0000	94	30	1. No damage to the panel was observed. 2. The coating was badly deteriorated.
148-FG39-YE09C-BN03	90	28	1. No damage to the control panel was observed.
149-FG40-QE06C-BN05	97	28	1. No damage to the panel was observed.
150-FG41-XE11C-0000	90	28	1. No damage to the panel was observed.
151-BR60-00000-ALCO	108	28	1. The boron substrate was punctured. 2. A one and one-half inch diameter area of honeycomb core under the discharge was vaporized.
152-GP51-00000-ALCO	110	28	1. No puncture of the graphite substrate was shown; however, the surface of the substrate was burned.
153-FG39-00000-ALCO	158	Oscillatory	1. The fiberglass panels were blown off the honeycomb core which had a five inch diameter hole.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
154-GP52-N101C-0000	105	27	1. The front surface of the graphite substrate was slightly charred.
155-BR61-UE05C-0000	50	50	1. The substrate was severely damaged.
156-BR62-UE05C-KF01	50	50	1. The substrate was severely damaged.
157-BR63-UE05T-KF01	90	38	1. The substrate was severely damaged.
158-GP53-UE05T-KF01	100	26	1. The substrate was severely damaged.
159-FG43-UE05C-0000	120	Oscillatory	1. No damage to the fiberglas panel was observed.
160-BR64-DE10C-BN06	50	52	1. The substrate was severely damaged. 2. The coating was partially bubbled.
161-BR65-DE10C-KF01	44	52	1. The substrate was damaged, a few small holes were punctured.
162-FG44-UE05T-0000	100	Oscillatory	1. No damage to the fiberglas panel was observed.
163-BR66-DE10C-0000	50	50	1. The substrate was severely damaged.
164-BR67-UE05T-0000	110	Oscillatory	1. The substrate was severely damaged.
165-BR68-DE10T-BN06	102	28	1. The substrate was severely damaged.
166-BR69-DE10T-0000	110	28	1. The substrate was severely damaged.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
167-BR70-DE10T-KF01	104	27	1. No visible damage to the substrate was found. 2. Surface flashover was shown.
168-GP54-UE05C-KF01	92	31	1. The substrate was severely damaged.
169-GP55-DE10C-KF01	83	35	1. No visible damage was observed to the neighboring area of the initial discharge spot; however, due to the surface flashover, the arc reattached to the edge of the panel and damaged the fiber along the edge.
170-GP56-UE05C-0000	98	30	1. The substrate was severely damaged.
171-GP57-DE01C-0000	94	34	1. The edge of the substrate was damaged as the arc flashed over the coating surface and reattached to the edge.
172-GP58-DE10C-BN06	100	30	1. The substrate was severely damaged.
173-GP59-DE10T-BN06	104	29	1. The substrate was severely damaged.
174-GP60-DE10T-KF01	100	32	1. No damage to the substrate was observed. 2. Surface flashover was shown.
175-GP61-DE10T-0000	103	28	1. The substrate was severely damaged.
176-GP62-UE05T-0000	98	27	1. The substrate was severely damaged. 2. Bubbled coating surface.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
177-GP63-00000-ALCO	106	22	1. The graphite substrate was punctured. 2. Aluminum honeycomb core was partially burned.
178-BR71-CW02P-0000	70	32	1. The substrate was severely damaged.
179-FG45-CW02P-0000	100	23	1. No damage to the panel was observed.
180-BR72-KF01C-ALCO	100	26	1. The boron substrate was pitted and punctur~d with small holes. 2. Aluminum honeycomb core was partially burned.
181-GP64-UE07T-KF03	104	22	1. No damage to the substrate was observed except for a crack at one edge; however, this crack was probably mechanical damage caused by the collision between the test panel and the mounting frame. 2. Arc flashover pattern was shown.
182-BR73-UE07T-KF03	100	30	1. No damage to the substrate was observed except for a crack at one edge; however, this crack was probably mechanical damage caused by the collision between the test panel and the mounting frame. 2. Arc flashover pattern was shown.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
183-GP65-ZE06T-KF01	92	28	1. No damage to the substrate was observed except for a crack at one edge; however this crack was probably mechanical damage caused by the collision between the test panel and the mounting frame. 2. Arc flashover pattern was shown.
184-BR74-ZE06T-KF01	100	25	1. No damage to the substrate was observed. 2. Arc flashover pattern was shown.
185-GP66-PE14T-KF01	112	21	1. No damage to the substrate was observed. 2. Arc flashover pattern was shown.
186-BR75-DE10T-EP11	85	30	1. No damage to the substrate was observed. 2. Arc flashover pattern was shown.
187-GP67-DE10T-EP11	90	30	1. No damage to the substrate was observed. 2. Arc flashover pattern was shown.
188-GP68-DE05T-KF01	94	26	1. The substrate was severely damaged.
189-BR76-DE05T-KF01	93	25	1. No damage to the substrate was observed. 2. Arc flashover pattern was shown.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
190-BR77-DE07T-KF01	108	29	1. No damage to the substrate was observed. 2. Arc flashover pattern was shown, and a burned-off coating track was also shown.
191-GP69-DE07T-KF01	105	23	1. No damage to the substrate was observed. 2. Arc flashover pattern was shown, and a burned-off coating track was also shown.
192-BR78-PE14T-KF01	98	26	1. No damage to the substrate was observed. 2. Arc flashover pattern was shown, and a burned-off coating track was also shown.
193-GP70-SW08P-0000	90	25	1. The front surface of the substrate was charred and partially delaminated. 2. The netting was peeled off the substrate.
194-BR79-SW08P-0000	100	25	1. The netting screen was mostly vaporized. 2. A few small burned marks were observed on the front surface of the substrate.
195-BR80-VA05C-AF01	108	20	1. The substrate was damaged probably due to the high pressure shock wave.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
196-GP71-VA05C-AF01	106	20	1. Damaged substrate.
197-GP72-DE08T-KF01	110	20	1. No damage to the substrate was observed. 2. A small burned mark on left side was shown.
198-GP73-DE11T-EP05	94	24	1. The substrate was severely damaged.
199-BR81-DE08T-KF01	180	22	1. No damage to the substrate was observed. 2. Coating was partially burned.
200-BR82-DE11T-EP05	90	25	1. No damage to the substrate was observed. 2. Flashover pattern was shown.
201-GP74-EP10T-KF01	110	Oscillatory	1. No damage to the substrate was observed. 2. Flashover pattern was shown. 3. Coating was slightly burned.
202-BR83-DP10T-KF01	94	24	1. No damage to the substrate was observed. 2. Flashover pattern was shown.
203-FG46-DE10C-0000	N/A	N/A	Nondischargeable
204-FG47-DE10C-BN06	N/A	N/A	Nondischargeable
205-FG48-DE10T-0000	N/A	N/A	Nondischargeable

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
206-FG49-DE10T-BN06	N/A	N/A	Nondischargeable
207-GP75-AD08E-0000	90	22	1. The front surface of the substrate was burned.
208-GP76-AD16B-KF01	103	21	1. The front surface of the substrate was burned. 2. Surface flashover pattern was shown.
209-BR84-AD08E-KF01	90	23	1. No visible damage to the substrate was observed. 2. Surface flashover pattern was shown.
210-BR85-AD16B-0000	103	22	1. No visible damage to the substrate was observed. 2. Surface flashover pattern was shown.
211-BR86-AD12A-0000	106	22	1. No visible damage to the substrate was observed. 2. Surface flashover pattern was shown.
212-GP77-AD20B-KF01	106	21	1. The front surface of the substrate was burned.
213-BR87-AD20B-0000	100	22	1. No visible damage to the substrate was observed. 2. Surface flashover pattern was shown.
214-GP78-AD12A-KF01	98	21	1. The front surface of the substrate was burned.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
224-GP82-AD08F-0000	100	22	1. The front surface of the substrate was charred; however, the substrate was not punctured.
225-BR94-AR16W-0000	360 coulomb 150 coulomb	1.5 sec. 1.0 sec.	1. Heavily burned substrate. 2. Hot spot was formed on the back side of the substrate.
226-GP83-AR04Z-0000	16 coulomb	0.1 sec.	1. Charred front surface of substrate; however, it was not punctured.
227-GP84-AD08E-KF03	100	22	1. No visible damage to the substrate around the neighboring area of the discharge was observed; however, the arc reattached to the edge of the substrate and damaged a part of the fibers.
228-BR95-AF03P-0000	170	19	1. No visible damage to the substrate was observed. 2. A surface flashover pattern was shown.
229-GP85-AF03P-0000	170	19	1. Charred substrate surface, no puncture.
230-GP86-CR04Z-0000	154	19	1. Lightly charred substrate surface.
231-BR96-CR04Z-0000	170	20	1. No puncture. 2. A surface flashover pattern was shown. 3. Deteriorated substrate due to high surface heating.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
215-GP79-AD12F-KF01	110	20	1. The front surface was pitted and slightly burned.
216-BR88-AD12F-0000	110	21	1. No visible damage to the substrate was observed. 2. Surface flashover pattern was shown.
217-BR89-AM04H-0000	88	23	1. No visible damage to the substrate was observed except for a small burned mark.
218-BR90-AD08E-0000	65	26	1. No visible damage to the substrate was observed. 2. A surface flashover pattern was shown.
219-GP80-AD08B-EP10	82	25	1. Damaged substrate.
220-BR91-AD08B-0000	85	25	1. No visible damage to the substrate was observed.
	65	40	1. The substrate was partially damaged.
221-GP81-AD08G-EP10	100	23	1. Damaged substrate.
222-BR92-AD08G-0000	95	23	1. No visible damage to the substrate was observed.
223-BR93-AD08F-0000	98	22	1. No visible damage to the substrate was observed.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
232-BR97-AD08G-0000	176	19	1. A small hole was punctured. 2. A surface flashover pattern was also shown.
233-BR98-AR08X-0000	200	40	1. No visible damage to the substrate was observed.
234-GP87-AR08X-0000	178	18	1. No visible damage to the substrate was observed.
235-AL01-00000-0000	215	30	1. No puncture; however the panel was dented.
236-BR99-AD086-0000	150	23	1. The substrate was punctured.
237-GP88-AD08G-0000	170	23	1. The substrate was severely burned. 2. A surface flashover pattern was shown.
238-BR00-AM04H-0000	155	24	1. The substrate was punctured with a small hole.
239-AL02-00000-0000	263 coulomb	1.5 sec.	1. The panel was burned through with an approximately 1-inch diameter hole.
240-GP89-AR08X-0000	400 coulomb	1.5 sec.	1. The substrate was burned through with a roughly 3/4" diameter hole.
241-BR01-AR08X-0000	500 coulomb	2.0 sec.	1. The substrate was burned through with an estimated 1-1/2" diameter hole.
242-GP90-AF01/2C-0000	100	18	1. The substrate was damaged.
243-BR02-AF01/2C-0000	100	18	1. The substrate was slightly damaged.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
244-GP91-FE03Y-0000	100	20	1. The substrate was severely burned.
245-BR03-FE03Y-0000	90	24	1. The substrate was slightly damaged.
246-GP92-CR07X-0000	223 coulomb 25 coulomb	1.7 sec. 0.25 sec.	1. The substrate was severely damaged. 2. The substrate was slightly burned.
247-GP93-AR16W-0000	89 coulomb 29 coulomb	0.7 sec. 0.3 sec.	1. The substrate was severely damaged. 2. No damage to the substrate was observed.
248-BR04-CR07X-0000	81 coulomb 61 coulomb	0.64 sec. 0.4 sec.	1. No noticeable damage to the substrate was observed for either test.
249-GP94-AR06U-KF03	44 coulomb 44 coulomb	0.42 sec. 0.32 sec.	1. The surface coating was severely pitted. No damage to the substrate was observed.
250-BR05-AR06U-KF03	69 coulomb	0.45 sec.	1. The surface coating was severely pitted. No damage to the substrate was observed.
251-GP95-AR04Z-0000	290 coulomb	1.5 sec.	1. The substrate was severely burned.
252-BR06-AR04Z-0000	26 coulomb	0.33 sec.	1. The substrate was not punctured even though it was heavily burned.
253-GP96-00000-0000	150	24	1. The panel surface was scorched.
254-BR07-DE07C-KF01	64	40	1. The substrate was severely damaged.
255-BR08-DE11C-EP05	110	24	1. The substrate was severely damaged.
256-GP97-DE10C-EP11	98	30	1. The substrate was severely damaged.

PANEL NO.	DISCHARGE CURRENT I (KA)	DISCHARGE DURATION T (μS)	RESULTS
257-BR09-DE10C-EP11	90	38	1. The substrate was severely damaged.
258-GP98-00000-0000	184	21	1. The substrate was severely damaged.
259-BR10-00000-0000	175	25	1. The panel was shattered.
260-GP99-AR04Z-0000	200	20	1. No damage to the substrate was observed. 2. A surface flashover pattern was shown.
261-BR11-AR04Z-0000	200	21	1. The substrate was punctured with several small holes.

One graphite panel was subjected to a 184 KA discharge as shown in Figure 11. This panel displayed resin scorching and severe delamination but no gross changes in the visible mode of damage. A 150 KA discharge was directed toward a 12 x 12 inch five ply graphite laminate (Panel No. 253). Some delamination of the outer plies and slight puncture of the panel was observed. The damage was the same degree as would have been expected to a 6 by 12 inch composite and indicates damage to graphite is independent of panel size.

For comparable lightning discharge currents the progression of damage is: boron > graphite > aluminum. This is shown in Figures 10, 11 and 12. Whereas the boron panel was completely shattered, the graphite panel was only punctured. The aluminum sheet was dented and noticeably mauled at the test zone. It should be noted also that the impedance of a boron/epoxy composite is almost 50 percent higher than that of a graphite/epoxy composite.

Uncoated panels were also tested in a sandwich panel configuration. Aluminum honeycomb core was bonded to the composite panels, i.e., glass, boron and graphite, with BMS 5-29 adhesive. A glass reinforced flat laminate was employed as the opposite skin to yield a closed cell configuration and to maximize any damage which might result from explosive vaporization of the aluminum core. The boron and graphite sandwich panels were mounted to the Faraday Cage in the normal test configuration. The core of the glass sandwich panel was grounded and a 1/2 inch diameter hole was cut through the face sheet. This test configuration provided direct attachment of the discharge arc to the core as the dielectric properties of the glass reinforced skin prevented normal discharge. Discharge to this panel damaged only the aluminum honeycomb core. The test result is shown in Figure 13. The upper left and center panels are the glass fabric reinforced face sheets. The hole is clearly visible on the labeled face sheet. The damaged core is shown at the bottom left hand side of the figure. The core was severely distorted due to expansion of the gases within the sandwich panel and a sizeable amount of aluminum was vaporized.

The uncoated boron sandwich panel (Panel No. 151, Figure 14) was cracked along the two fiber axes to within about 1 inch of each edge. A 1-inch square hole in the boron laminate coupled with extensive delamination was observed. Approximately 8 square inches of aluminum core were vaporized under the discharge zone and much of the boron skin was debonded from the core. No evidence of current conduction by the boron was present. Damage to the composite face sheet appears to be due to:

1. Arcing of the discharge through the composite to the aluminum honeycomb core, followed by

2. Explosive vaporization of the aluminum causing extensive composite face sheet cracking and delamination.

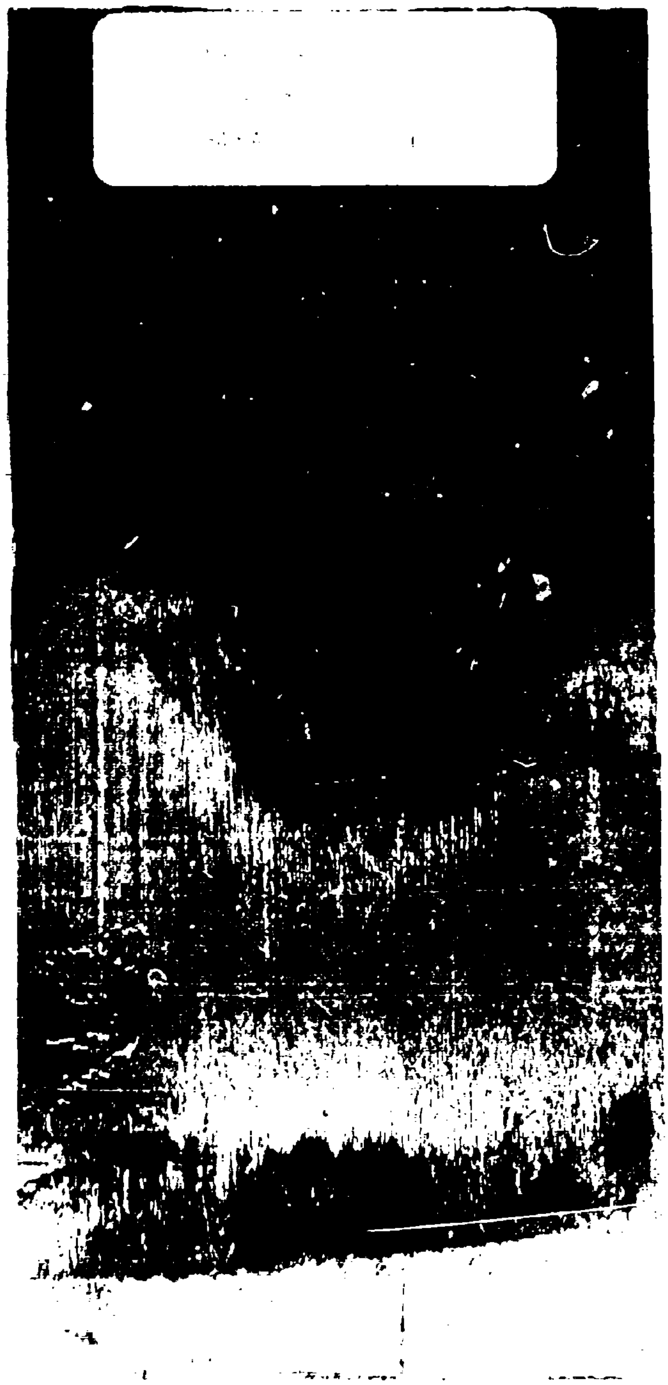


Figure 11 — [illegible]

Figure 12 HIGH CURRENT DAMAGE TO ALUMINUM SHEET

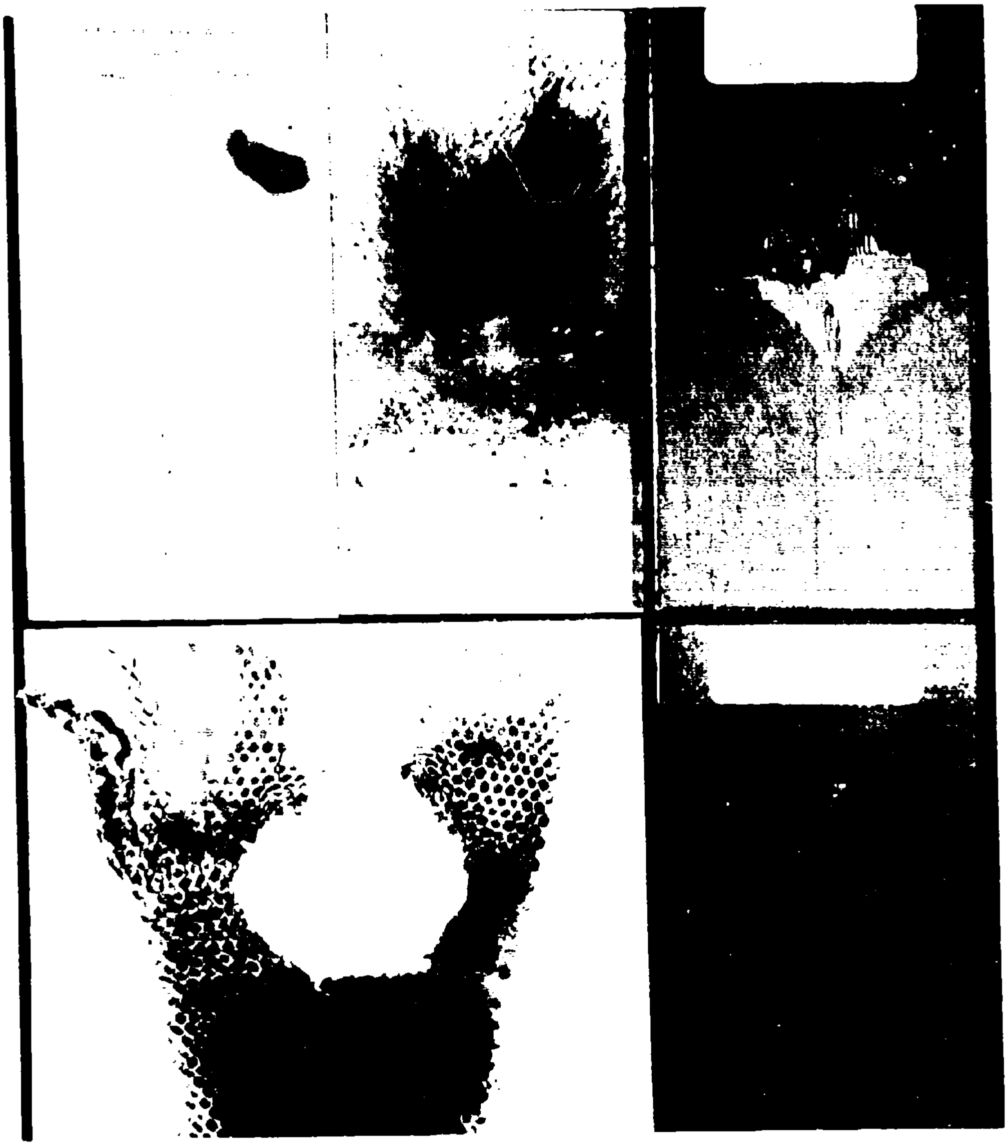
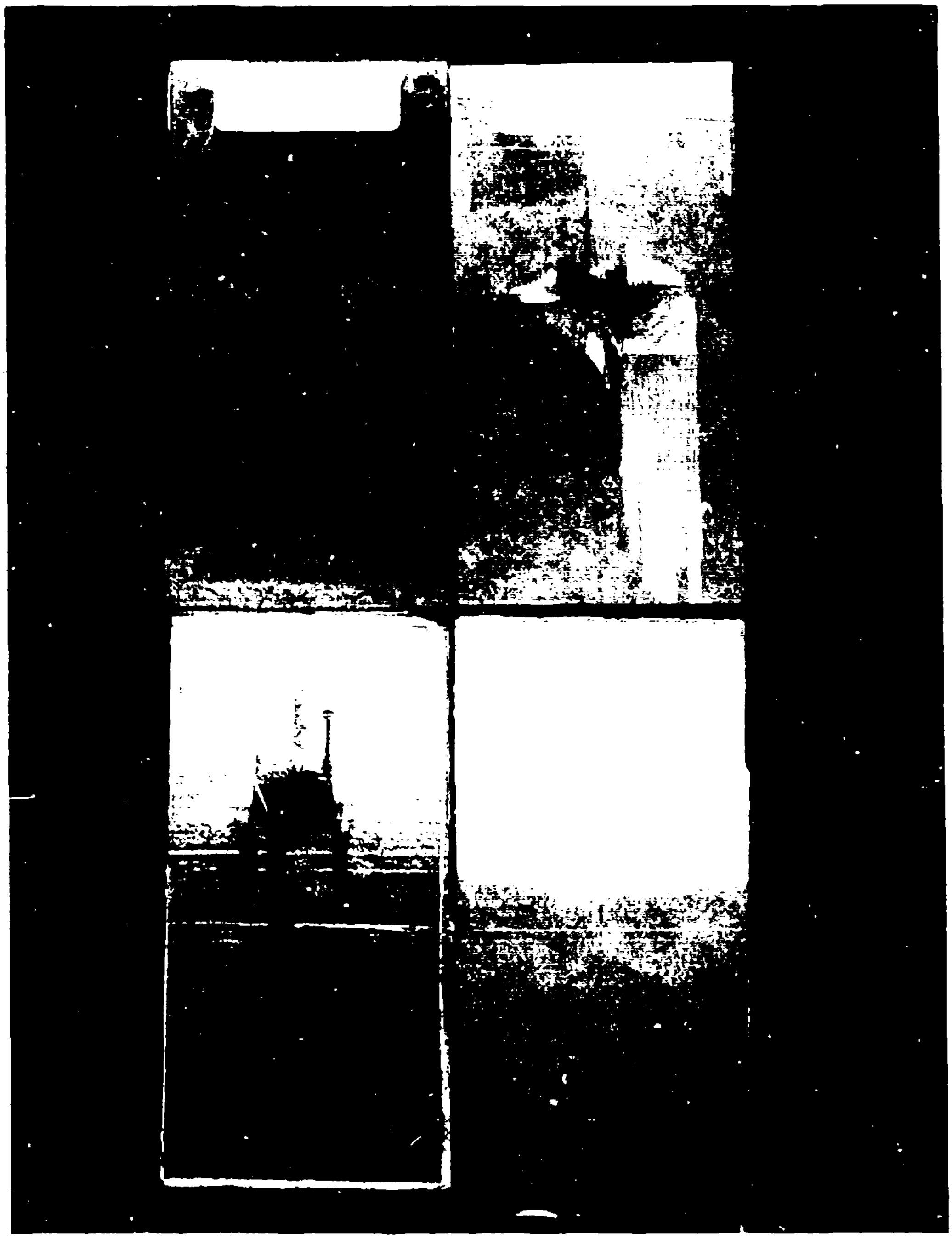


Figure 13 LIGHTNING DAMAGE TO [illegible]COATED SAN[illegible]



Little evidence of electrical damage to the boron was present.

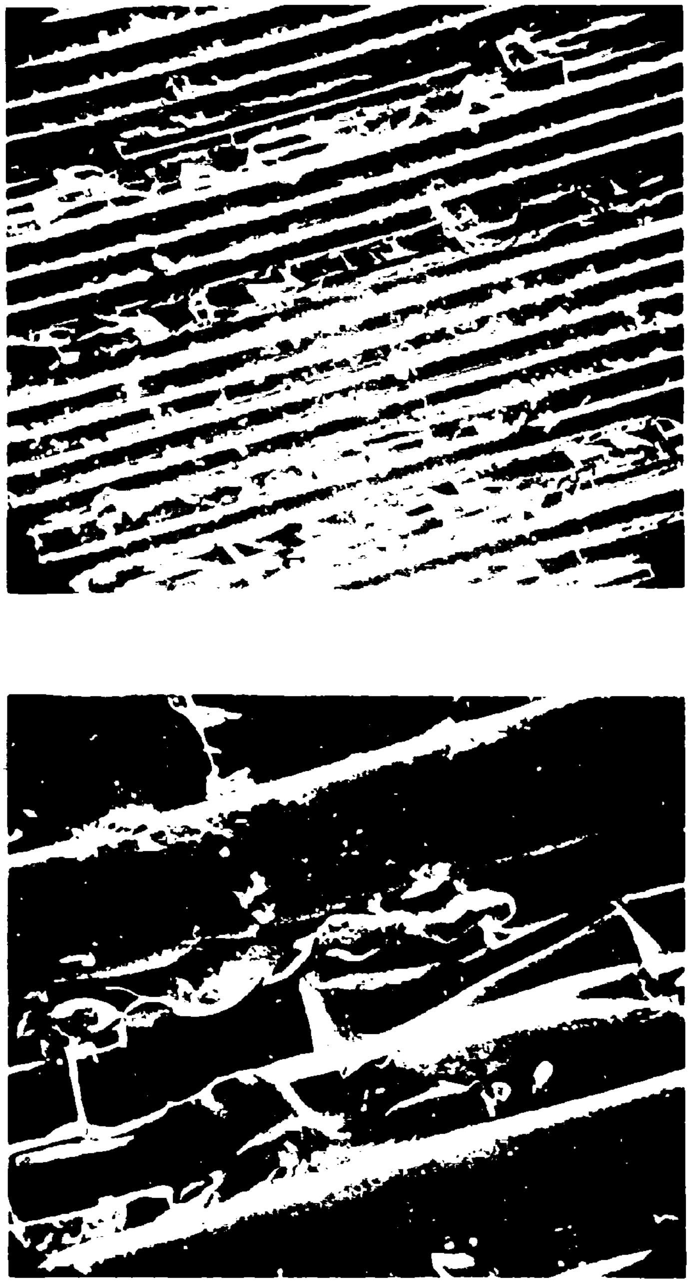
Another boron reinforced sandwich panel which incorporated a 1 mil thick insulative Kapton polyimide film between the two outer fiber plies is shown in Figure 14. Damage to this panel (No. 180) differed markedly from the previous panel (No. 151). The boron skin was pitted and punctured with several small holes, but no large puncture occurred. Additionally, while the core in the immediate discharge zone was slightly damaged, little aluminum core vaporization occurred. Current conduction by the boron fibers was readily apparent. A sizeable section of the skin could be delaminated by hand. The exposed area displayed several boron filaments which had split or been peeled apart.

Scanning electron microscope pictures (Figure 15) of these fibers illustrate damage to the boron filaments. Figure 15a illustrates the longitudinal weakness of some of the boron filaments. Upon peeling the delaminated face sheet by hand, several filaments were fractured along their entire length. A close-up view (Figure 15b) illustrates a damaged filament between two intact filaments. The tungsten core of the fiber, the white section in the damaged area, appears normal, i.e., it has not been explosively vaporized. The adjacent fibers are intact and display no cracks or other evidence of damage. The core of the filaments appears uniform and homogeneous. No evidence of melting or vaporization of this material can be discerned. Apparently these filaments were weakened by thermal stresses but were not heated to the melting point (1970-2150°C). The fact that some filaments are damaged while others are not indicates not all filaments carried the same current loads.

From these test results it is apparent that the presence of a one mil Kapton film results in a higher fiber current conduction. While these fibers conduct the discharge current away from the discharge zone, resistance heating damages the filaments. The resultant stresses cause filament rupture primarily along the fiber axis.

A sandwich panel incorporating a graphite reinforced face sheet was also tested (Panel No. 177). The graphite face sheet as shown in Figure 14 was punctured by the discharge arc and a minor amount of local damage to the core was observed. The effect of one mil Kapton film sandwiched between the outer plies of graphite fibers was also examined. This panel (No. 152) displayed extensive resin scorching laterally, but no puncture. These results illustrate the greater ability of graphite to dissipate intense electrical energy. Whereas, the boron sandwich panel was extensively damaged by explosive vaporization of the core, the graphite panel was primarily damaged by resin scorching due to fiber current conduction.

It can be concluded that the insulative layer of Kapton film did much to prevent damage to the aluminum honeycomb core by forcing most of the current into the fibers. This is possible because the dielectric breakdown strength of the epoxy matrix of the high modulus composite is much less than that of the Kapton polyimide film. Therefore, it is reasonable to assume that the current passes from one fiber to another



(a)

(b)

Figure 15. SEM VIEWS OF LIGHTNING DAMAGED BORON FILAMENTS

by a series of spark gaps. This has the effect of increasing the number of current carrying members, and thus reduces the amount of current carried by individual fibers. As a result, the simulated lightning discharge is dissipated to ground through an enormous number of conducting fibers and damage will be primarily located in the outer fiber ply. No explosive vaporization of aluminum honeycomb core occurs since the discharge arc does not penetrate the face sheet of the sandwich panel.

The argument for the damage preventing mechanism of Kapton film undercoating holds true for both graphite and boron; however, the important distinction of the fewer number of boron fibers, their lower conductivity, and the insulative boron sheath over each fiber tend to reduce Kapton's ability to limit current conduction to the outer plies of fibers. It is presumed that a balance can be reached to yield a condition that the destruction of the boron filaments by the high current densities produces arcing between fibers while the dielectric properties of the Kapton film impart an intraply directionality to the arcing. The result will be the localization of damage in the outer ply or plies, with little current penetration to the interior of the substrate.

5.1.2 Metal Foil Coated Composites

An initial series of tests were conducted to determine the effectiveness of continuous metal foils and tapes as lightning protective devices for advanced composite materials. The metal foil was aluminum in 1, 2, 3 and 6 mil thicknesses and provided 100 percent coverage of the composite surface. In the simulated lightning test, all of these foils were successful in preventing puncture of the boron or graphite laminates. The foils were vaporized at the contact point and sizeable areas of composite surface were left bare following a 100 kiloampere discharge. The size of the vaporized aluminum spot is inversely proportional to the aluminum thickness. For 90-100 KA discharges, a one mil foil would display a 2 to 2-1/2 inch diameter hole, whereas, for 6-mil foil, the hole was approximately one inch in diameter. This is shown in Figure 16.

All of these tests were also conducted employing glass fabric reinforced epoxy substrates. In this case the results were comparable, indicating the metal foil was accepting the high current levels in a normal fashion and its performance was not altered by the high modulus reinforcing fibers.

No difference in the damage to boron composite panels was observed when the aluminum foil was applied to the boron side or to the fiberglas scrim cloth side of the prepreg.

At the discharge level, i.e., 100 KA, the epoxy glass scrim cloth layer offers no additional protection to the composite. This result was also observed in the tests involving a Kapton dielectric layer between the composite and the aluminum foil. Visible damage to the Kapton film undercoat was minimal or nonexistent. The metal foil was able to dissipate the energy of these discharges and prevent current penetration into the boron or graphite fibers.

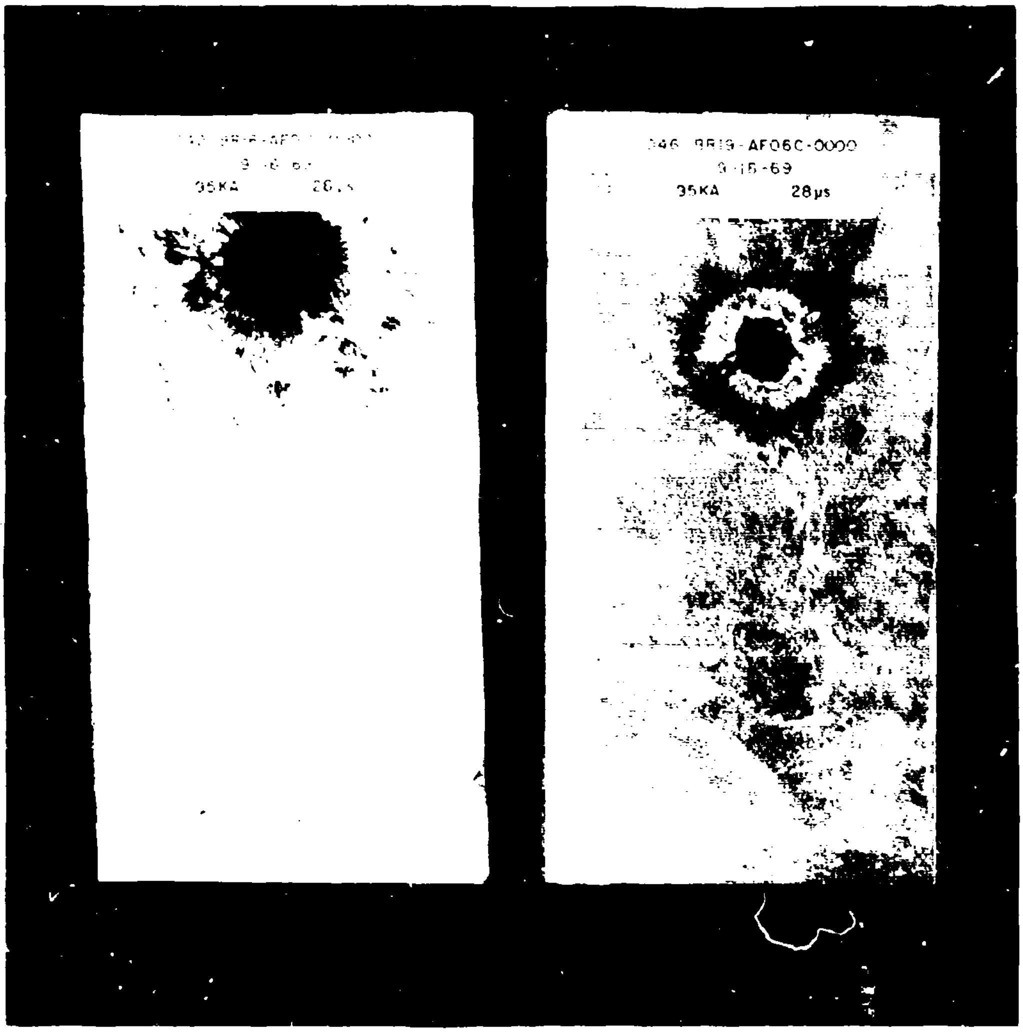


Figure 16. LIGHTNING DAMAGE TO ALUMINUM FOIL COATED BORON EPOXY COMPOSITES

Evidence of high current concentrations at the outer edges of the panels was displayed in Panel 036. Figure 17 shows the burn spots which occasionally occur at the edges of the panels. In addition, some panels displayed a large area of fused aluminum near the electrical ground terminal.

Panels subjected to two successive discharges of 100 KA have shown the one mil aluminum foil can withstand restrikes if the second contact point is directed to an undamaged area of the remaining aluminum surface (Figure 18, Panel 043). In this case, the panel was first tested with the initial discharge located approximately at the center and three inches from one end of the panel. The initial discharge vaporized a two inch diameter circle of aluminum but no visible damage to the composite occurred. The panel was then mounted and retested; in this test configuration, the previously vaporized aluminum hole was placed between the discharge probe and the ground (for detailed test setup, refer to Section 3). The second discharge also vaporized a two inch diameter circle in the foil at the contact point. In addition, this discharge vaporized the aluminum which remained between the original circle and the panel edges.

One half mil (0.0005") thick aluminum foils were not successful in preventing damage to the composites. Some resin scorching at the contact zone was noted for both panels. Excessive current conduction by the boron fibers of the outer plies was suspected. It was concluded that 1 mil aluminum foil is the minimum thickness required. This is shown in Figure 19 for 100 KA discharge protection.

The lack of transverse strength in unidirectional composite panels is displayed in Figure 20. Panel 041, a unidirectional laminate, was cracked down the fiber axis. Panel 042, a bi-directional laminate, showed no cracking or back side damage but a comparable amount of foil damage. It is concluded that fiber orientation does not alter the protection efficiency of metal foils.

Lightning strike damage to the aluminum foils protecting boron and graphite composites is comparable. Graphite laminates displayed minor areas of fiber-resin debonding at the center of the strike zone however. This effect was increased through the use of thicker aluminum foils. Apparently, the thicker foil is capable of dissipating more of the charge, but concentrates more heat energy in the same area or maintains a high temperature condition for a longer time. These thick foils provided evidence of resin scorching on both boron and graphite laminates. The full structural effects of this scorching have not been evaluated.

Sandwich panels with aluminum core and boron epoxy or graphite epoxy face sheets are also protected by one mil thick aluminum foil coatings. The test results shown in Figure 21 illustrate that neither the front nor back side received damage when tested with both the coating and the core grounded. The damage to the coating was comparable to that displayed by flat laminates. No damage to the boron or graphite panels was visible to the eye in either case. The aluminum foil can withstand

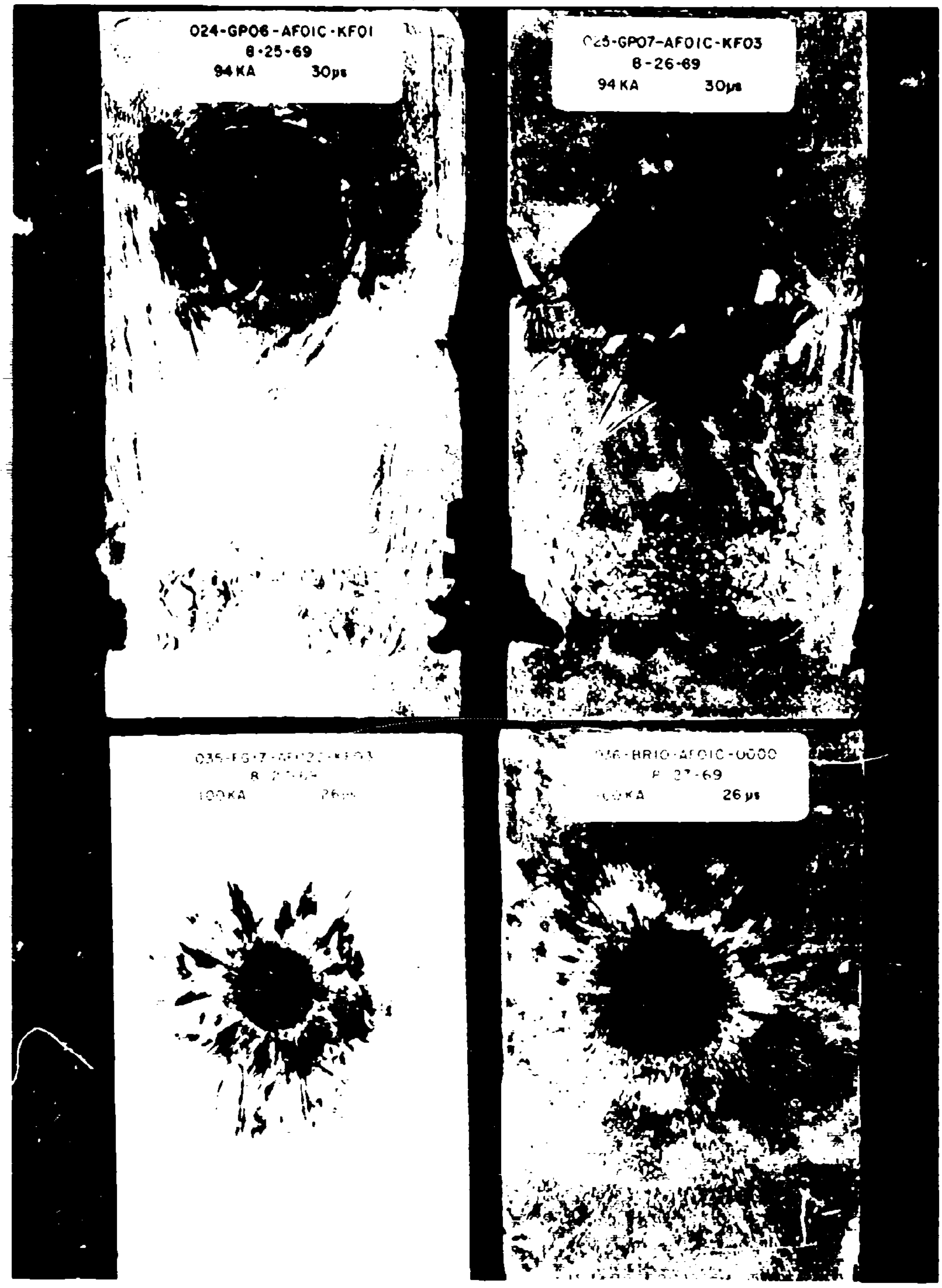


Figure 17 LIGHTNING DAMAGE [illegible] COMPOSITES

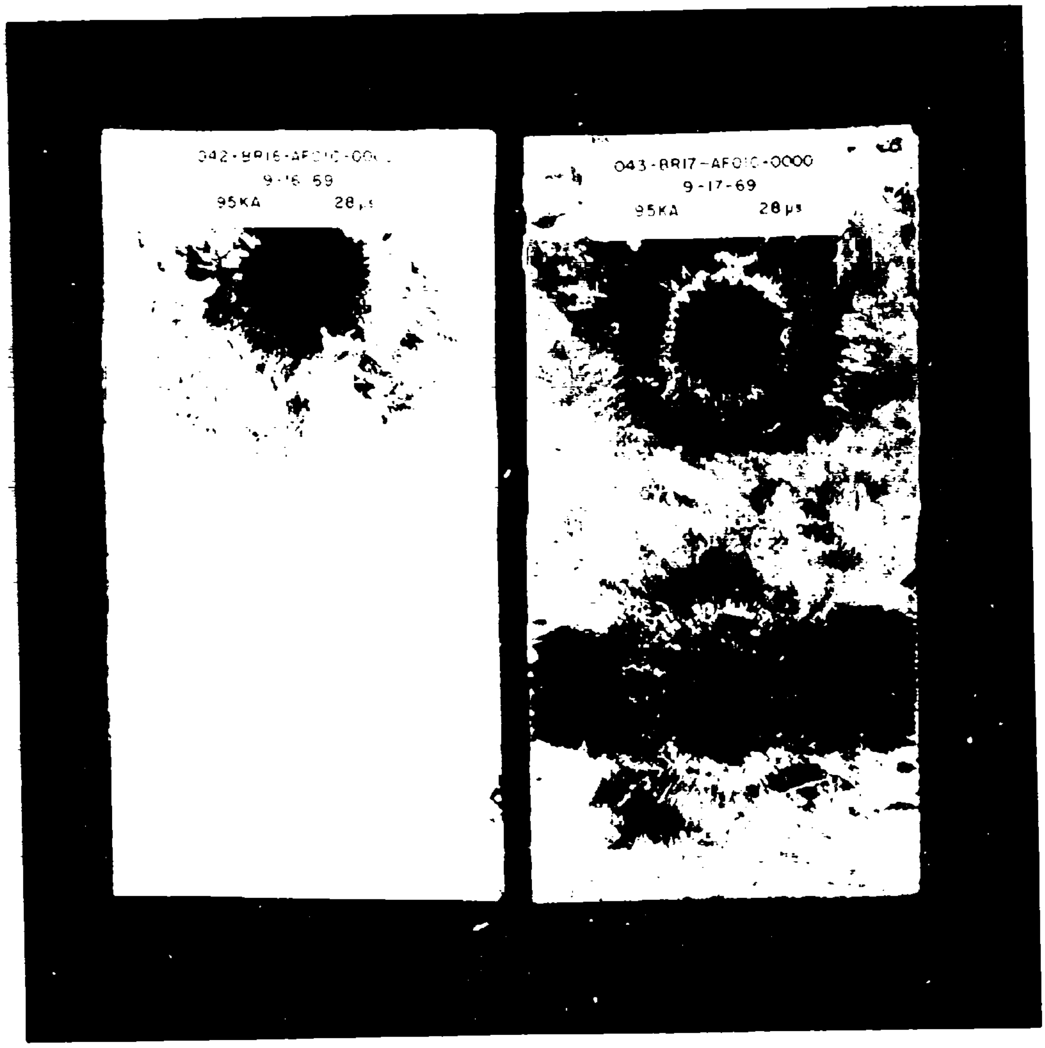


Figure 18: RESTRIKE DAMAGE TO ALUMINUM FOIL COATED BORON EPOXY LAMINATE

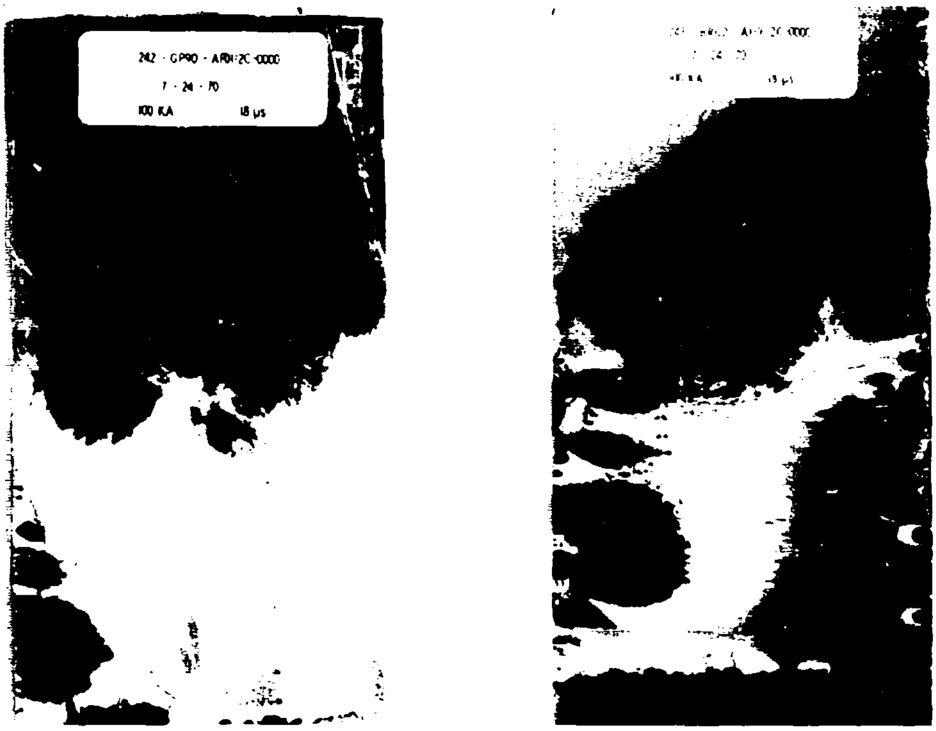


Figure 19: *LIGHTNING DAMAGE TO THIN FOIL COATED BORON/EPOXY AND GRAPHITE/EPOXY LAMINATES*

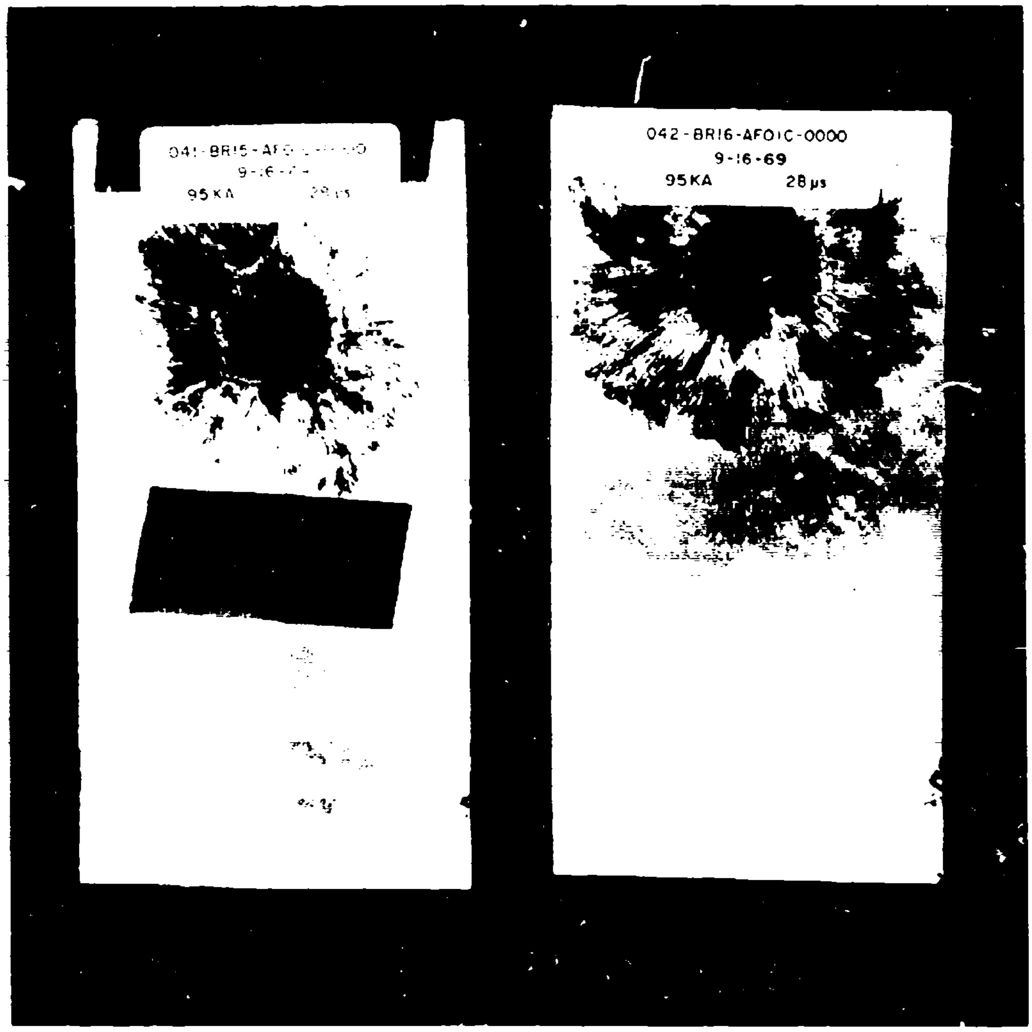


Figure 20 EFFECT OF FILAMENT ORIENTATION ON LIGHTNING DAMAGE TO FOIL COATED BORON EPOXY LAMINATES

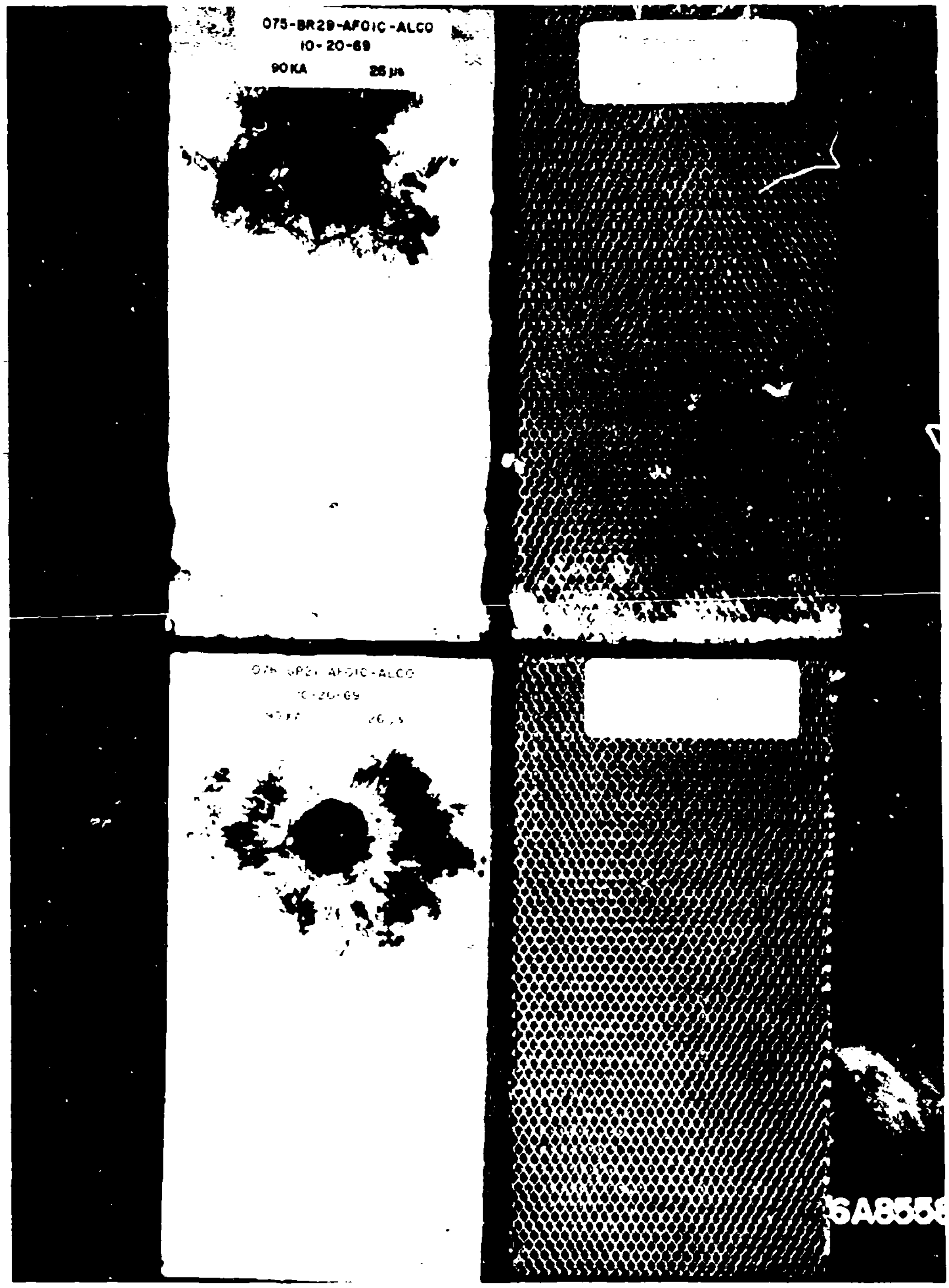


Figure [illegible] DAMAGE TO ALU[illegible] [illegible]
[illegible] PANEL FACE SHEET

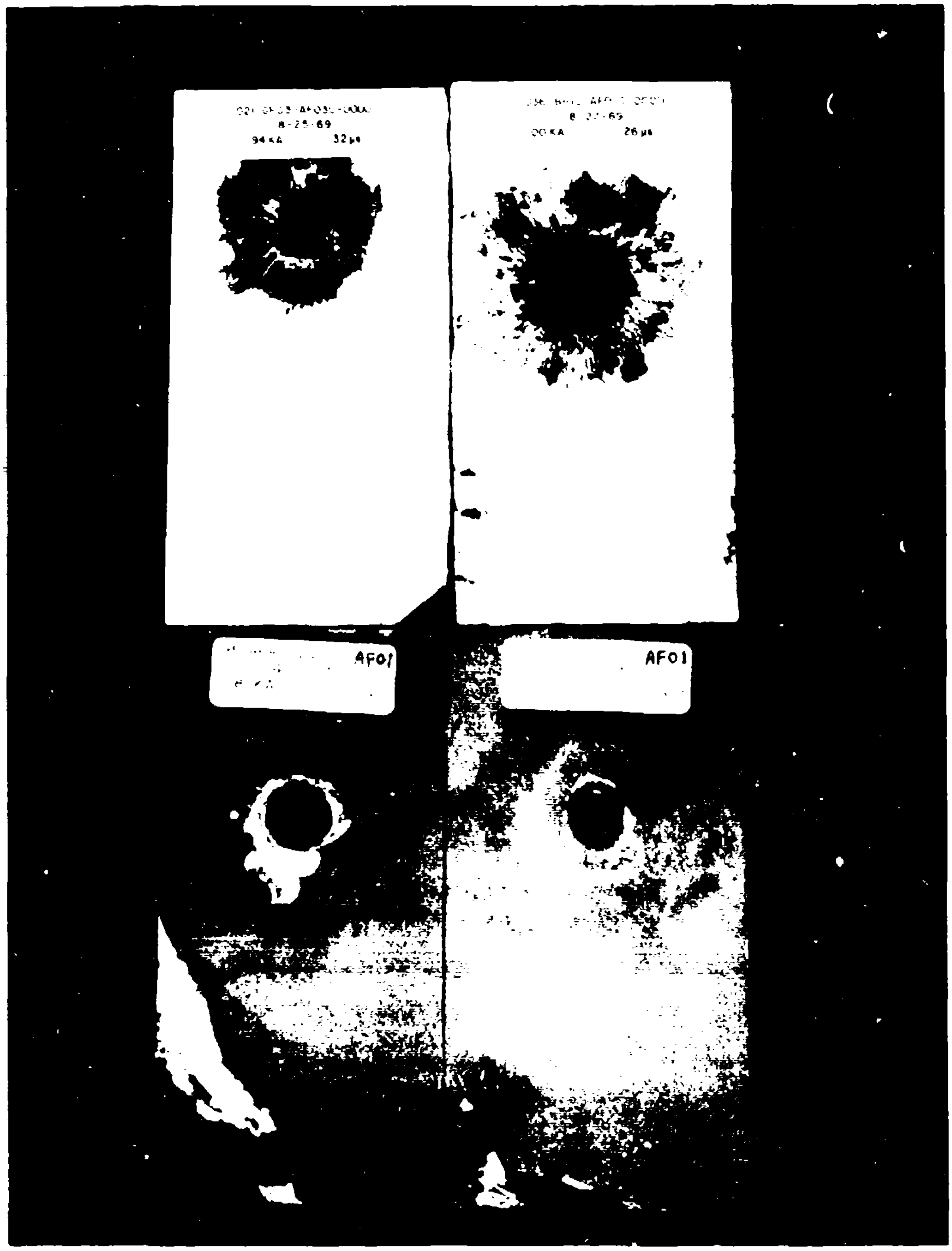
the 100 KA discharge for a time long enough to prevent attachment of the arc to the composite material. Damage in these tests was thus limited to the surface coating only.

Two additional aluminum foil coated panels (No. 195 and 196) were tested. These results are illustrated in Figure 22. The 1-mil thick foils that provided complete coverage of the composite panels were integrally bonded to the composite during panel cure. A 0.3-mil primer coat and a 3-mil topcoat of Dynacryl vinyl acrylic paint were applied over the aluminum foil. The object of this test was to ascertain that with environmentally stable coatings the lightning protection efficiency of the aluminum was not significantly different from that observed on simple aluminum foils (Panel No. 021 and 036, Figure 22). The major distinction between the two systems is the "halo" effect observed on bare aluminum due to metal vaporization. The painted aluminum displays a ragged, peeling type of damage. This is due to surface topcoat confinement of the pressure from aluminum vapor. This confining force is not large enough to cause mechanical damage to the composite but can lead to additional local heating. These results indicate that environmentally protective coatings can successfully be applied over lightning protective coatings with a minimal loss of lightning protection efficiency.

Other metal foils were investigated, also. A one-half mil thick continuous nickel foil was nearly destroyed by the discharge, but quite successfully protected a boron reinforced panel from 100 KA discharge currents (Panel No. 116, Figure 23). Although a slight darkening occurred at the discharge arc contact point, the epoxy under this was not visibly damaged. However, half mil nickel foil was not as successful in protecting graphite composites (Panel No. 115, Figure 23). The foil was delaminated from the panel, torn near the ground connection and severely discolored. A three-inch diameter mark on the substrate was burned at the discharge point though no back side damage was visible. A 1-mil thick nickel foil was also integrally bonded to a graphite reinforced laminate (Panel No. 154). The thicker foil displayed good protective qualities and prevented current penetration to the graphite reinforcing fibers. Damage was limited to the vaporization of a small area of the nickel foil.

In summary, a 1-mil nickel foil behaves much the same as aluminum foil when employed as a lightning protective device; a 1 mil thick foil is required to provide a protective coating for boron and graphite substrate at a moderate 100 KA discharge. One-half mil thick nickel foils provide good lightning protection qualities to boron but not graphite reinforced composites.

Two mil copper foils (Panel No. 099, 101) behave much like comparable thickness aluminum foils in the protection they offer to boron and graphite reinforced plastics (Figure 24). At 100 KA discharge levels, foil damage was restricted to the vaporization of a circle approximately one and a half inches in diameter and no damage to the substrate under the vaporized foil was observed. The rough edge of the circle has peeled away from the composite and displays heat discoloration. Burning and vaporization of the metal at the ground connection also occurred and



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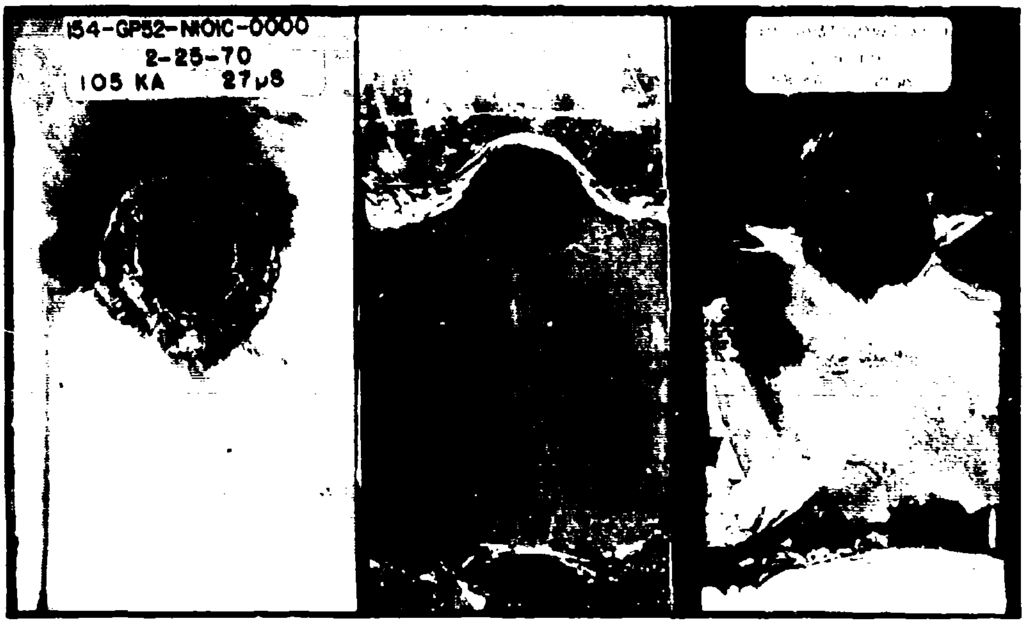


Figure 23: *LIGHTNING DAMAGE TO NICKEL FOIL COATED HIGH MODULUS COMPOSITES*

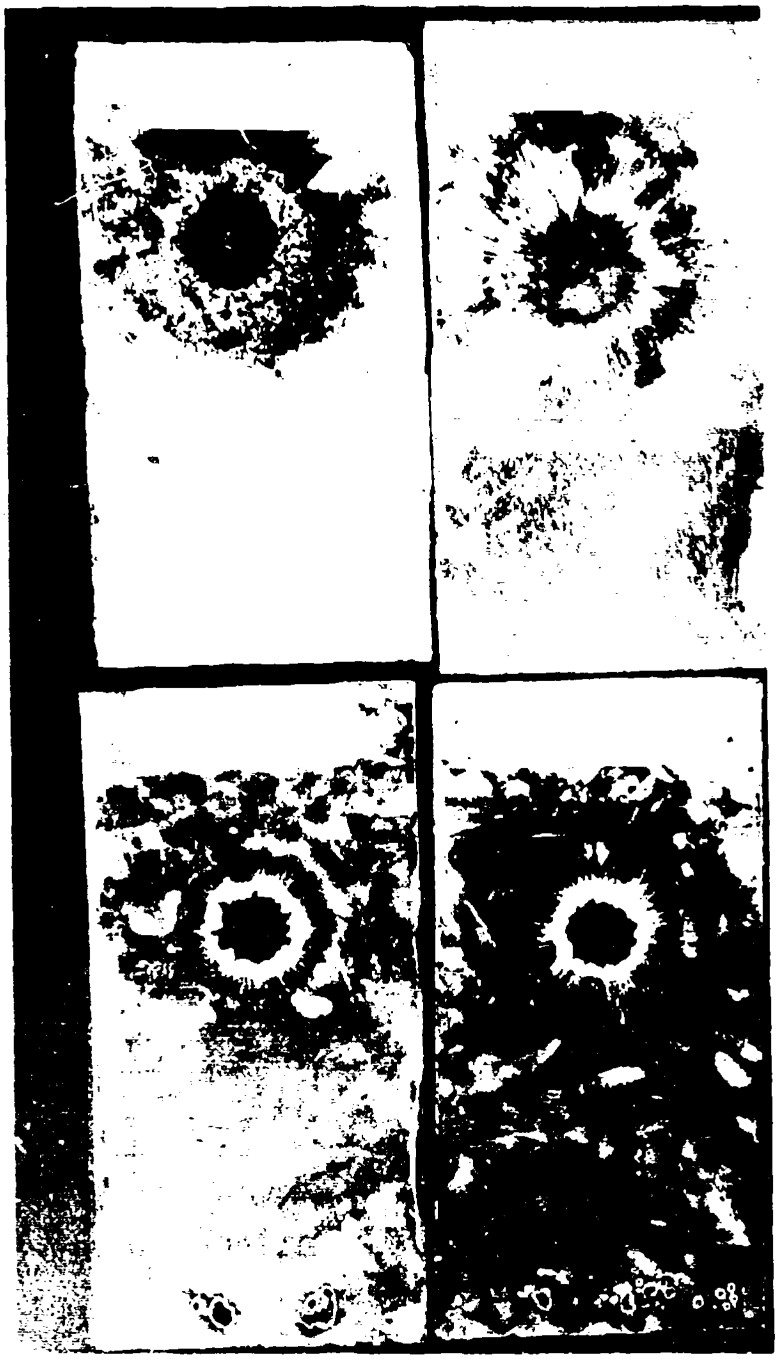


Figure 24. LIGHTNING DAMAGE TO ALUMINUM AND COPPER FOIL COATED COMPOSITES

resulted in a series of small holes in the foil; however, the epoxy matrix under these holes was not damaged. In comparison with aluminum foils, the additional conductivity of copper does not markedly improve its lightning protection characteristics, and the higher density of copper yields a weight penalty. This weight penalty exists for all conductive metals and their alloys, except aluminum.

5.1.3 Expendable Metal Strip Coatings

Metal protective strips have also effectively protected the composites from a lightning discharge. One inch wide, 3-mil thick tapes were bonded to the periphery of the panel and down the center (Panel No. 020, 049, Figure 25). The discharge was directed to the center tape. The aluminum tape was severely damaged by the discharge, the center tape being both vaporized and blown from the panel. Damage was not restricted to this center tape, however. Bubbling at tape lap joints and peeling at corners was observed. This indicates that the current was carried to ground by all three of the tapes and not by just the center one. Some arcing from the center to the two edge tapes occurred as evidenced by the scorching of the resin and vaporization of metal along the inside edges of the two edge tapes opposite the probe. Amazingly, except at the top joints, the conductive adhesive which bonded these tapes to the laminates was unharmed. The resin was still tacky and the embedded copper particles were visible to the naked eye. Panel 049 (Figure 25) utilized a continuous 6-mil thick aluminum foil about the periphery and down the panel center. Discharge damage was much less than that displayed by the 3-mil aluminum tape of Panel 020. Other foil geometries displayed the same effect and none gave evidence of damage to the boron or the graphite. Evidently a continuous path to ground is a preferred protective system.

One inch wide, 3-mil thick aluminum strips were also tested at a 170 KA discharge level as shown in Figure 26, Panels 228 and 229. The strips were bonded around the panel periphery and one strip was along the 12-inch panel center. Discharge was directed toward this center tape. The tapes themselves were completely destroyed by this discharge, while the graphite fiber reinforced laminate was badly scorched on the front surface. Apparently this type of metal geometry or the method of bonding (rubber based adhesive) does not impart sufficient dissipation characteristics. This method is also rejected on the basis of the large open areas left on the panel surface. These tests have shown that metal geometry can force the discharge current along directional pathways without increasing composite damage or reducing metal effectiveness.

5.1.4 Wire Fabric Coatings

The success of aluminum metal foils as a lightning protective coating for boron fiber and graphite fiber reinforced composites prompted the study of other continuous metal systems. One method of providing a continuous conducting member is to utilize a woven wire fabric or a knitted wire mesh as the conductor. Such systems can be easily incorporated into advanced composite design and manufacture. Development of this concept focused first on single wires and very heavy fabrics. This effort was

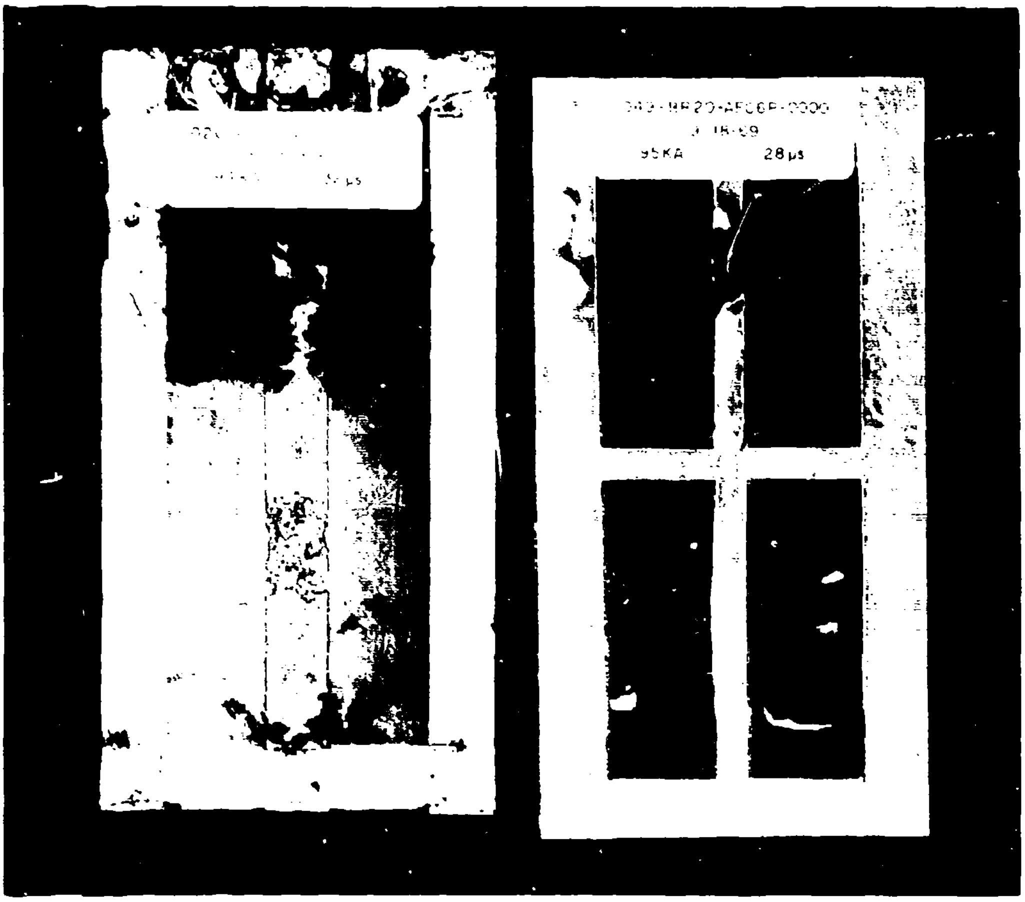


Figure 25: LIGHTNING DAMAGE TO EXPENDABLE METAL STRIP COATINGS

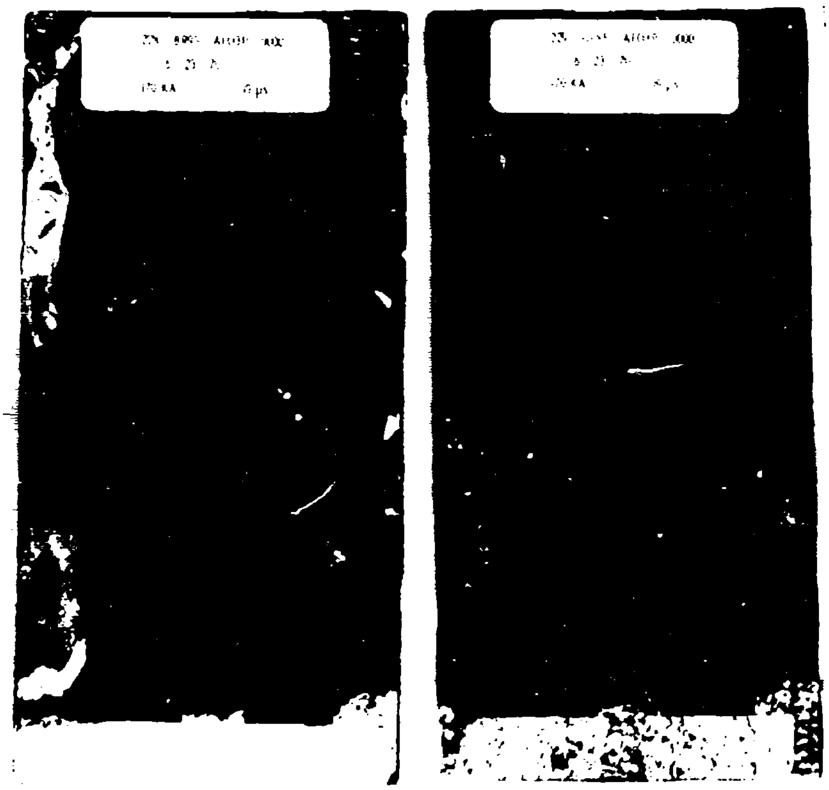


Figure 26. HIGH CURRENT DAMAGE TO EXPENDABLE METAL STRIP COATINGS

then refined to determine the suitability of finer wire fabrics and metals other than aluminum.

Control tests employing 2-mil diameter copper wires have shown wire density to play an important role in the protection performance of wire fabric coatings. Wires were bonded to test panels such that the inter-wire spacing was 1/2-inch along the 6-inch direction and 2 inches along the 12-inch direction. Each wire was individually bonded with a bead of BMS 5-29J, a room temperature curing epoxy-polyamide. The boron panel (Panel No. 96) as shown in Figure 27 was completely fractured along the 6-inch direction at the arc attachment point and also from this point to the end away from ground; the panel was also completely severed across the 6-inch dimension approximately 1 inch and 2 inches away from ground. These fractures are not too obvious in Figure 27. In addition a 1/2-inch wide and 5-inch long strip of composite was completely destroyed at the arc attachment point. All of the wires between the stroke attachment and ground were vaporized as was some of the resin used to bond wires. The graphite panel (Panel No. 100) was extensively delaminated near the attachment point and nearly severed at a point 3 inches nearer ground. The grounded wires were completely destroyed, while the orthogonal ones were not. Evidence of extensive resin scorching and fiber conduction was present. It was obvious that the graphite fibers carried more of the current load than did their boron counterparts. The copper wires were very efficient in conducting current away from the attachment point, but not of sufficient number and/or size to prevent damage to the composite.

An additional boron panel (Panel No. 178) as shown in Figure 28 was also tested. This panel was a standard 5-ply flat laminate with the outer ply oriented along the 6-inch panel edge in contrast to the previous panels which had the outer fiber plies oriented along the 12-inch direction. With the outer fibers oriented in the 6-inch direction, none of them traced a path to electrical ground; in effect, the outer fiber ply should act as an insulating layer in this test configuration. A 70 KA discharge was initiated to this test panel. Damage was observed to be in the form of several cracks along the full 6-inch width. This appeared to be due to intense local heating and/or the explosive pressure of the copper wire. Damage to the panel was less than that observed previously, but the magnitude of the peak discharge current was also less (70 KA compared with 114 KA). Nevertheless, the wire density is insuficient to prevent structural damage to the boron composite.

A glass fiber reinforced panel (No. 179) was coated with copper wires in a similar fashion. Discharge to this panel left many of the wires at the edges still intact, but destroyed the wires as well as their resin binder which were more centrally located (Figure 28). The copper wires were very efficient in their prevention of damage to this panel. The type of behavior observed appears to be a combination of wire conduction coupled with some surface flashover to ground.

Figure 27 LIGHTNING DAMAGE TO COPPER WIRE AND BRONZE FABRIC COVERED BORON EPOXY AND GRAPHITE EPOXY LAMINATES

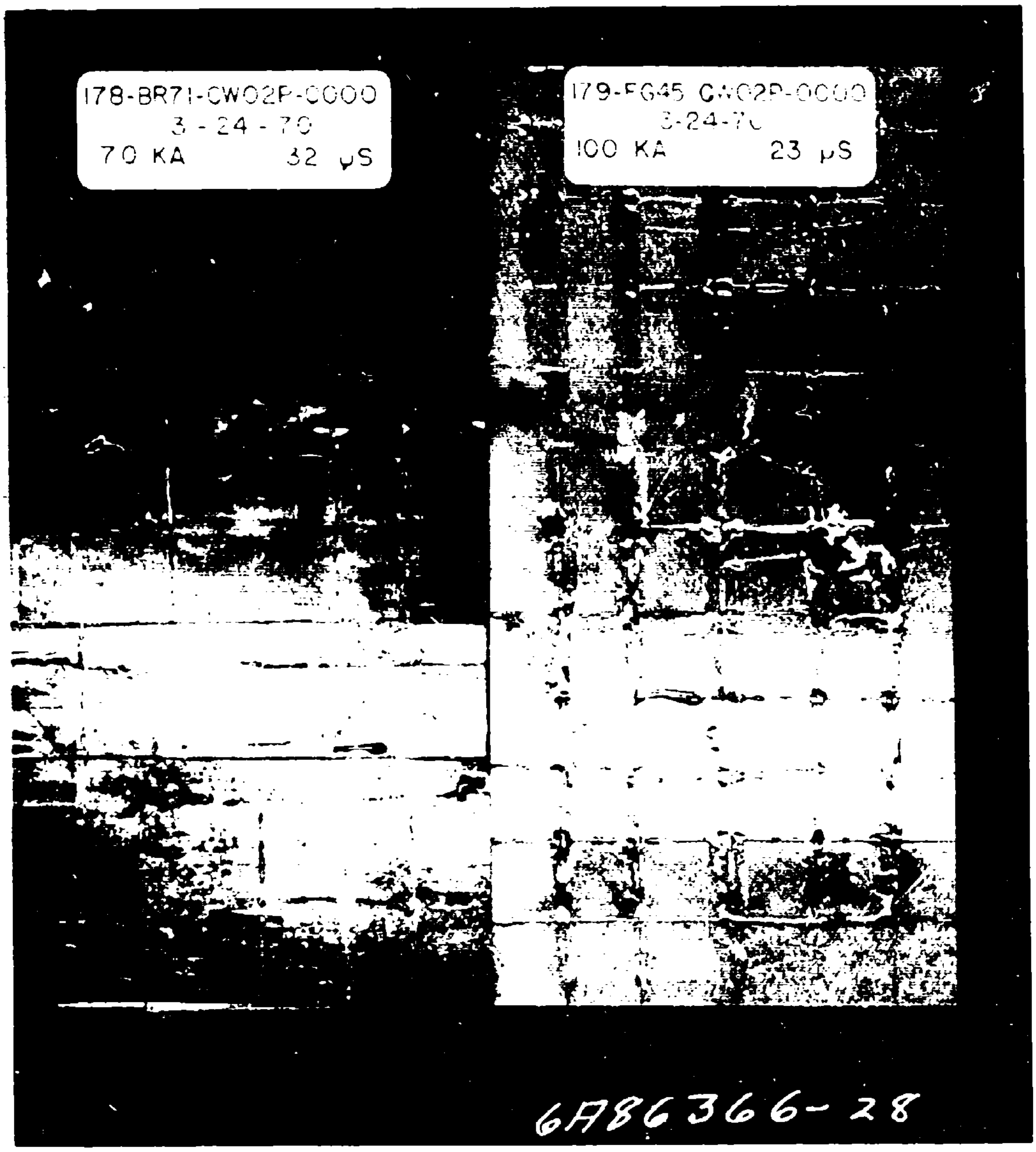


Figure 28 LIGHTNING DAMAGE TO BORON EPOXY AND GLASS REINFORCED CONTROL LAMINATES COATED WITH COPPER WIRES

These tests have shown that there are no inherent difficulties in the use of wire coatings. In fact the degree of damage to the composites must be considered very minimal in view of the nature of the coating. The wires appear to guide the lightning arc to the ground terminal with an amazing efficiency.

The next series of tests were designed to study the efficiency of woven wire fabrics. The first tests utilized a 60 by 60 mesh, 8-mil diameter, aluminum wire fabric which is equivalent in metal weight to 6.0-mils of continuous aluminum foil.

As expected, the 60 mesh aluminum fabric provided excellent lightning protection to boron (Panel No. 134) and graphite (Panel No. 135) reinforced laminates (Figure 29). The damage to the fabric closely resembled that observed for comparable metal foils. That is, the damage is limited to a small hole in the fabric at the discharge zone and some burning at the ground connection. No back side damage was recorded and very little scorching of the resin bonding the laminate and fabric occurred.

The same fabric was also applied in the form of a protective strip (Panel No. 136, 137 and 138). The discharge was directed to a 1/2 inch wide strip of fabric near the center of the laminate. The fabric axes were 45° with respect to the panel edge and no single wire traced a continuous pathway to ground. The discharge completely destroyed this center strip, but did not damage the reinforced epoxy substrate (Figure 29). A gray, smoke-like deposit remained over much of the panel surface and indicated that some arcing across the face to the outer productive fabric strips might have occurred. In these tests, the damage to the coatings on boron and graphite reinforced panels was comparable. Damage to the coatings over a glass reinforced epoxy appeared to be slightly less than the high modulus composites.

The test results of this same 60 by 60 mesh aluminum fabric with a two component discharge as shown in Figure 30 were surprising since the boron substrate was not burned through. The coated boron composite (Panel No. 225) received a total charge transfer of 360 coulombs and the result was a burned boron laminate which displayed a "hot spot" on the back side. Most of the aluminum was melted or vaporized away from the composite surface. A similar test at a lower coulomb transfer level caused a small hole to be burned through the graphite fiber reinforced composite (Panel No. 247). The high coulomb damage to both composites must be considered severe but the coating provided adequate protection against the high amperage component.

Boron fiber and graphite fiber reinforced composites were also coated with a finer, 120 by 120 mesh twilled weave aluminum wire fabric. This fine wire fabric employed a 4.0-mil diameter 5056 alloy wire and was bonded to the panels in a secondary bonding process using BMS 5-29, an epoxy-polyamide. This coating survived very high energy discharges with remarkably little damage to the coating or to the composite (Figure 31).

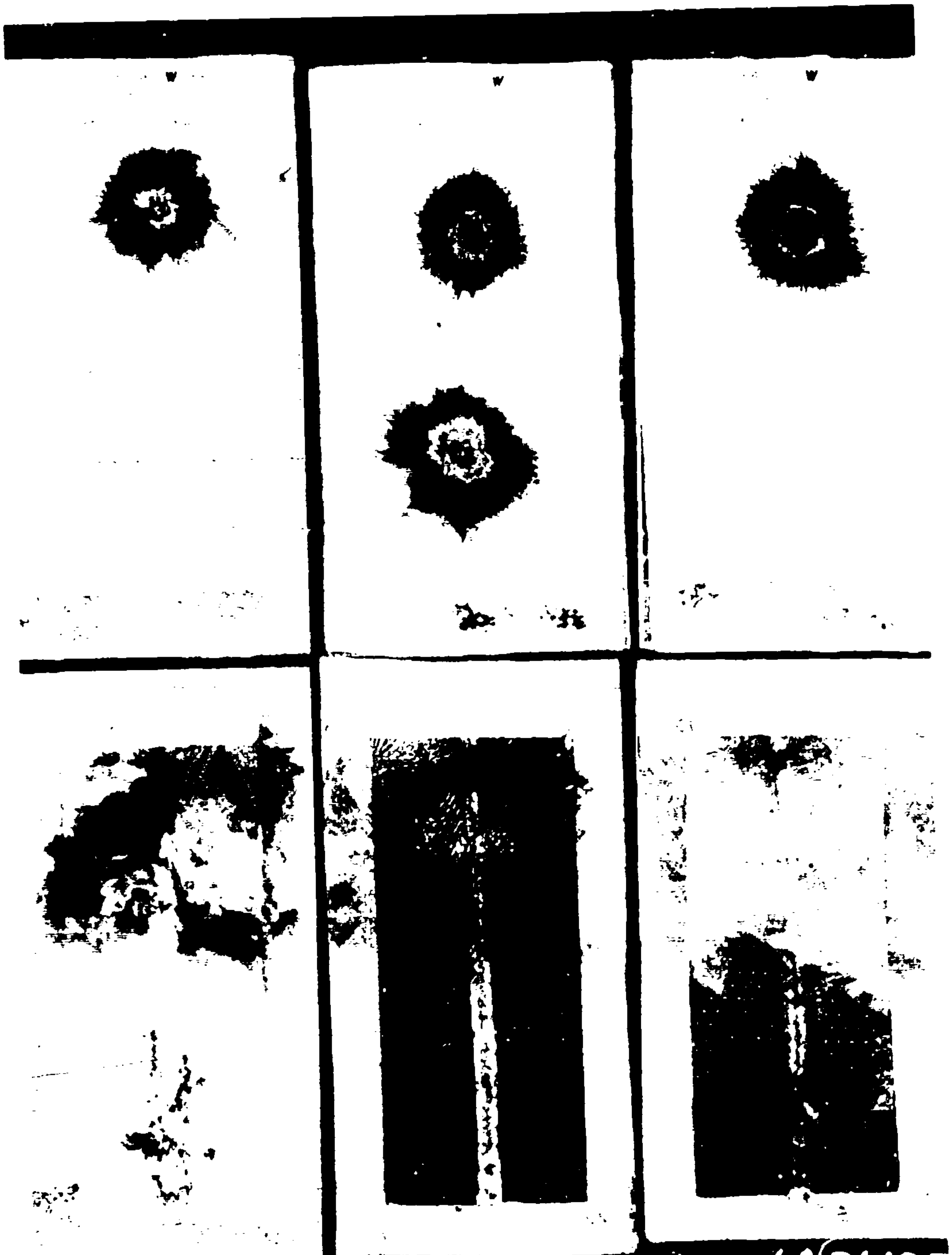


Figure 29 LIGHTNING DAMAGE TO COMPOSITE LAMINATES COATED WITH ALUMINUM WIRE FABRICS

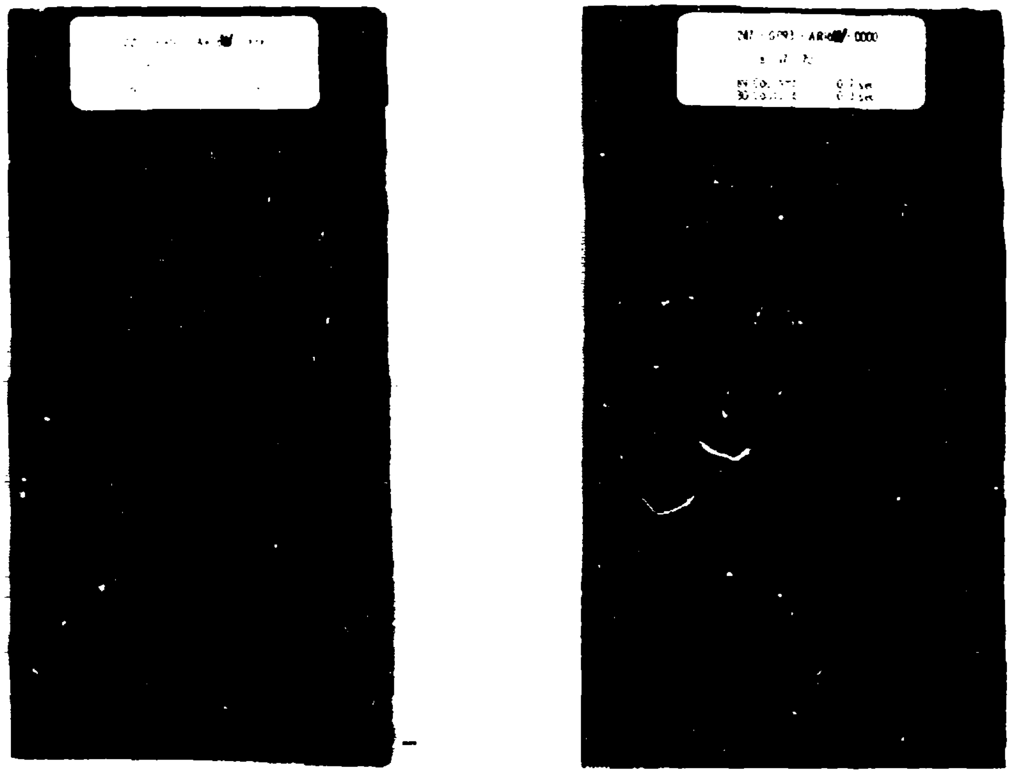


Figure 30: HIGH COULOMB DISCHARGE BURN DAMAGE TO ALUMINUM WIRE FABRIC COATED BORON/EPOXY AND GRAPHITE/EPOXY LAMINATES

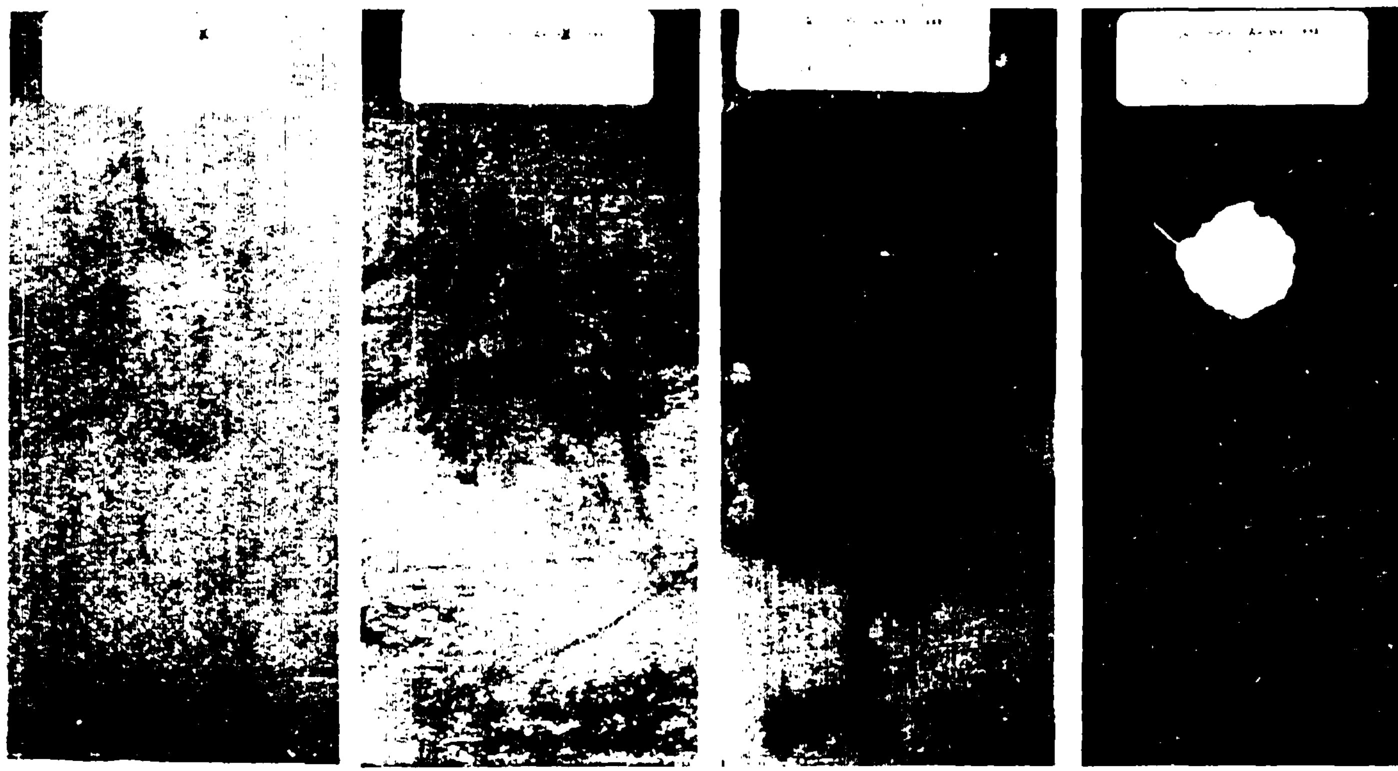


Figure 31. HIGH AMPERAGE AND HIGH COULOMB DAMAGE TO ALUMINUM WIRE FABRIC COATED COMPOSITES

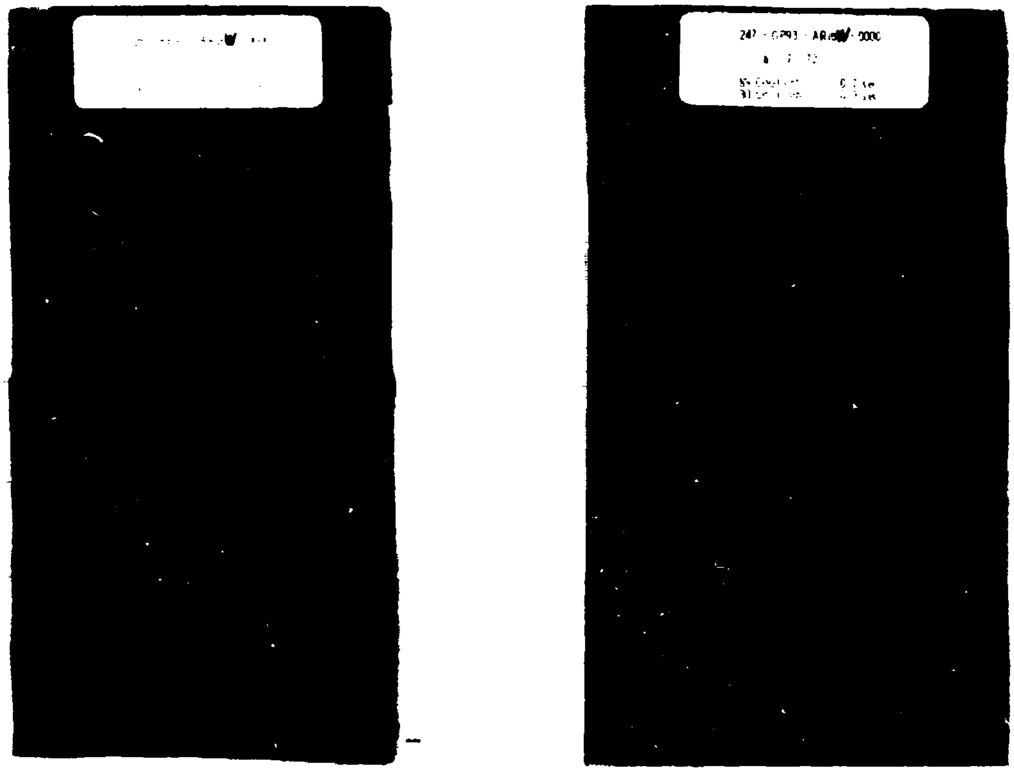


Figure 30. *HIGH COULOMB DISCHARGE BURN DAMAGE TO ALUMINUM WIRE FABRIC COATED BORON/EPOXY AND GRAPHITE/EPOXY LAMINATES*

Figure 31 HIGH AMPERAGE AND HIGH COULOMB DAMAGE TO ALUMINUM WIRE FABRIC COATED COMPOSITES

A 200 KA discharge to the boron fiber reinforced composite (Panel No. 233) damaged only the coating. Only a small pin-hole in the epoxy matrix could be detected in the composite. This may have been due to collision of the probe with the panel during discharge. When the same coating was tested over a graphite-fiber reinforced composite (Panel No. 234), the same result was obtained. A 178 KA discharge resulted in no evidence of damage to the composite although some of the fabric was burned away.

This same fabric was also tested under high coulomb transfer conditions. The coating was bonded to the composites in the same manner as above and covered the entire laminate surface. A 400 coulomb transfer test to the graphite fiber reinforced composite (Panel No. 240) was sufficient to burn a small hole through the laminate. The hole was conical shaped, being about 1 inch in diameter at the near side and about 1/2 inch in diameter at the back side. The fabric coating was damaged only in the direct vicinity of the hole, indicating the currents were carried by the fibers as well as the aluminum fabric. No evidence of flashover-type behavior was found.

Similarly, a 500 coulomb transfer test to a coated boron composite (Panel No. 241) burned a two inch diameter hole in the composite. Some evidence of boron filament damage along the arc contact-electrical ground line was visible. This included a mottled, 1/4 inch wide, brown discoloration of the composite along this axis. At the hole, resolidified boron, tungsten and aluminum were found in large globular masses at the edges.

An additional test as shown in Figure 32 of this type of wire fabric employed a 100 by 100 mesh, 3-mil twilled weave aluminum. A 3-mil Kapton film underlayer was also applied. Discharge to these panels (No. 249, 250) illustrated that the discharge arc extinguished itself after very low coulomb transfer to the composite. This was because the arc channel was forced to extend as the wire mass depleted and the generator voltage could only maintain a limited length of an air arc. However, this is indicative of excellent protection to the reinforcing fibers by the Kapton film and excellent current conduction of the aluminum. The wire fabric dissipated the current with some loss of wire due to vaporization. The Kapton dielectric assured that the arc was kept exterior to the composite substrate.

Two hundred mesh aluminum wire fabric (Panel No. 118, 123 and 124, Figure 33) provided exceptional protection to both the panel and the protective coating. Very little destruction of the wires was observed and that which did occur appeared randomly distributed about the discharge zone. In contrast to a 1-mil aluminum foil, much of the area near the discharge was still intact and could presumably conduct additional current loads. With both aluminum and phosphor-bronze fabrics, damage to the screen protecting graphite was more excessive than that protecting boron. This is possibly indicative of some current conduction by the graphite.

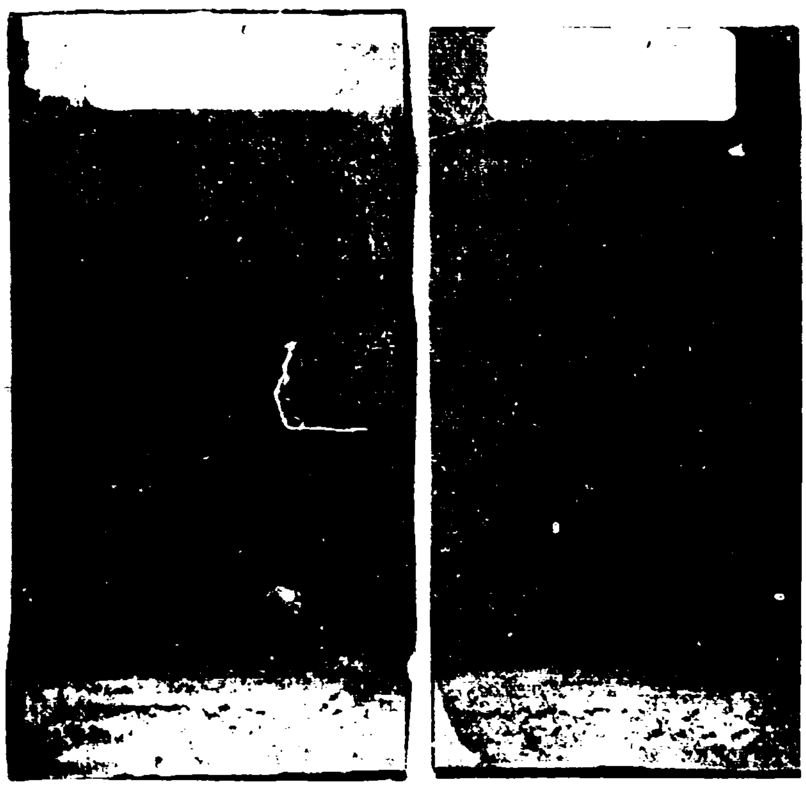


Figure 32: HIGH COULOMB DAMAGE TO ALUMINUM WIRE FABRIC KAPTON FILM COATED BORON/ EPOXY AND GRAPHITE/EPOXY LAMINATES

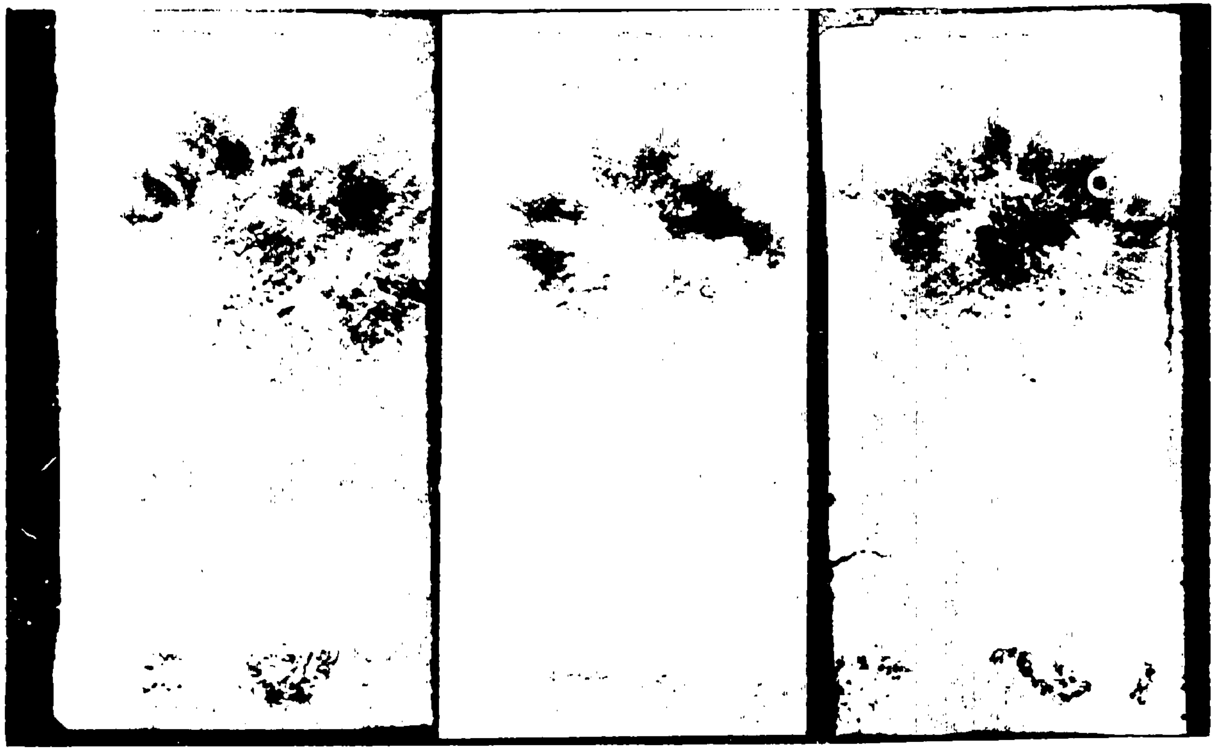


Figure 33. SIMULATED LIGHTNING DISCHARGE DAMAGE TO 200 BY 200 MESH ALUMINUM FABRIC COATED COMPOSITES

The graphite panel was tested twice. The discharge for the second test was directed to an undamaged portion of the fabric. The fabric was torn from the panel surface, but successfully dissipated the charge in both instances. In fact, the coating must be judged better than 1-mil thick aluminum foil especially when restrike protection is considered. It is important to note that the resin overlay does not impart structural damage to the composite because the exploding wires are not fully confined during the discharge.

Additional tests shown in Figure 34 at 200 KA have proven this coating concept to perform well even at extremely high discharge levels. A surface flashover pattern was evident for both panels. The boron fiber reinforced composite was punctured with a few very small holes however. No other damage to the panels was visible.

High coulomb transfer tests to panels as shown in Figure 35 coated with this wire fabric have also illustrated this system to perform well. Both boron fiber (Panel No. 252) and graphite fiber (Panel 251) reinforced composites were severely burned by this test, but neither was punctured. Damage to the boron fiber reinforced laminate was primarily to the coating and the first ply of reinforcing fibers. The damage was mostly thermal. The graphite fiber reinforced composite was delaminated and the first three plies of fibers were destroyed at the contact zone.

This system is considered to be the most promising of the continuous metal coatings available.

Other wire fabrics were also studied but found to be inferior to aluminum in terms of the conductivity/weight ratio. For example, a plain weave, 4.5-mil diameter wire, 100 mesh bronze fabric was able to withstand 100 kiloampere discharges with a minimum of damage to the fabric and no visible damage to the boron or graphite substrate. Figure 36 compares the damage to boron, graphite and fiberglas coated panels. In all cases, a 1 to 1-1/2 inch diameter hole was burned in the fabric although little damage was done to the epoxy adhesive underlayer. Panels 066, 077 and 178 displayed no damage to the fabric due to arcing between metal fibers. In these panels, no single wire traced a continuous path from the probe to ground. The burn marks at the bottom of these panels were introduced by arcing between the fabric and the copper braid used for the ground electrode. The highly reflecting areas of these panels are due to resin bleed-through.

A similar, but lighter bronze fabric was shown (Figure 37) to be moderately successful in dissipating high coulomb transfer currents. The fabric, a 120 by 120 plain weave utilized a 3.5-mil phosphor bronze wire. A 225 coulomb transfer component to the graphite fiber reinforced composite (Panel 246) burned through the outer three plies of the composite. The fabric dissipated much of the current. The result was further illustrated with the boron fiber reinforced laminate (Panel No. 248). In this case, damage was to the resin and the fabric. Little damage to the fibers were discernible.

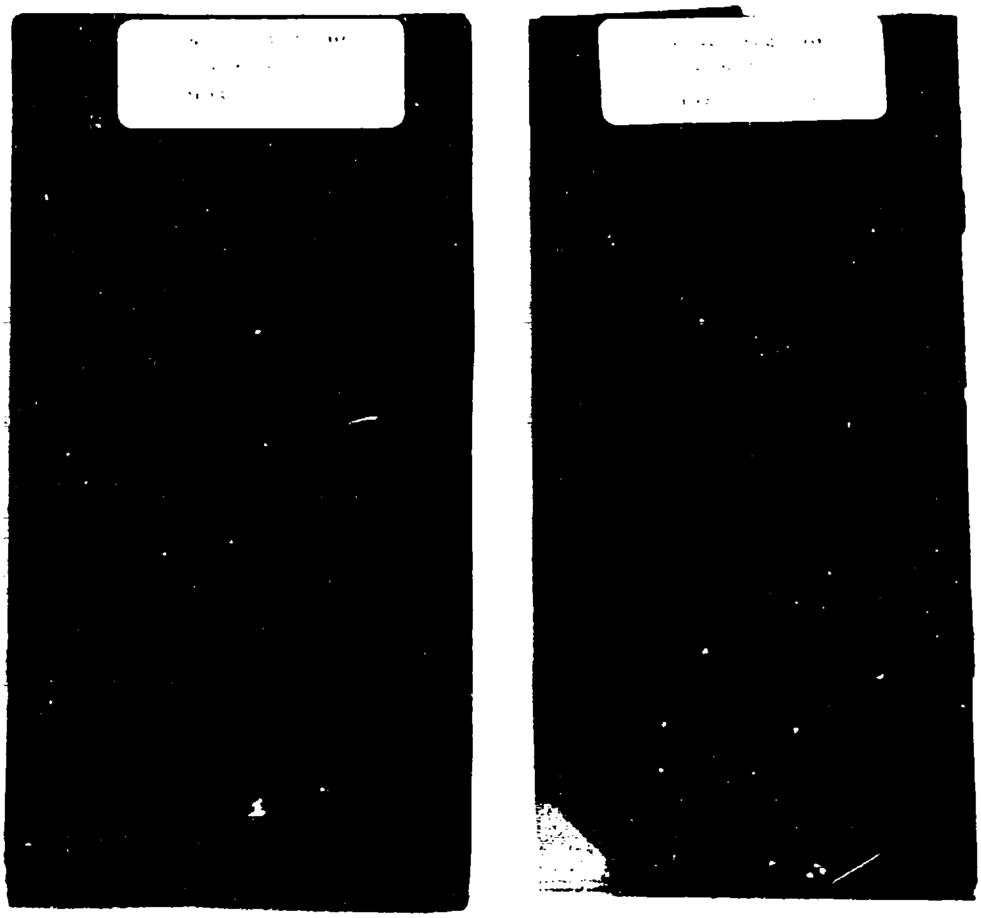


Figure 34 200 KA SIMULATED LIGHTNING DISCHARGE DAMAGE TO 200 BY 200 MESH ALUMINUM FABRIC COATED LAMINATES

Figure 35. HIGH COULOMB TRANSFER TEST DAMAGE TO 200 BY 200 MESH ALUMINUM FABRIC COATED COMPOSITES

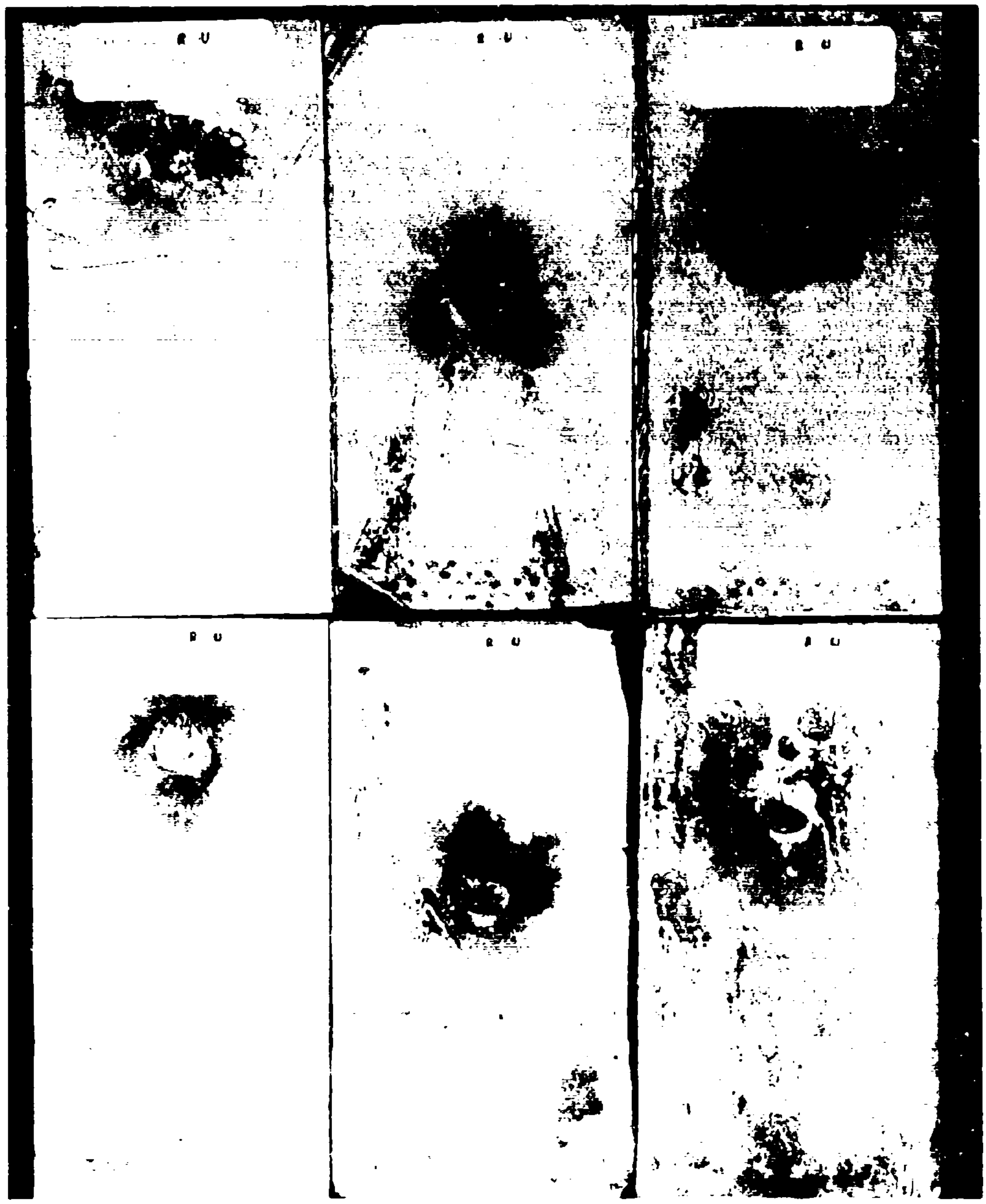


Figure 36 SIMULATED LIGHTNING DISCHARGE TO BRONZE WIRE FABRIC COATED COMPOSITES

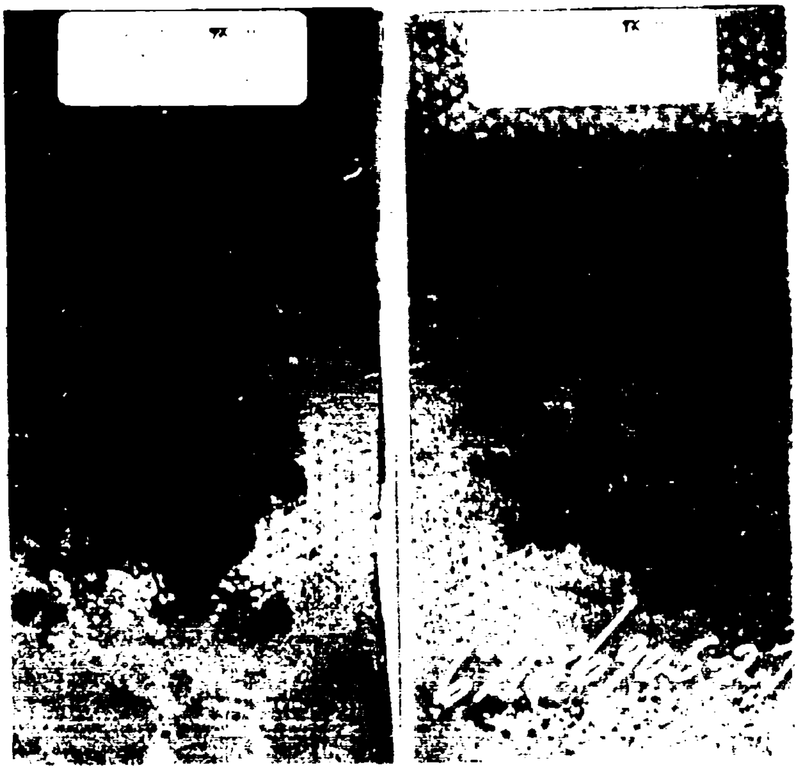


Figure 37   HIGH COULOMB TRANSFER TEST DAMAGE TO BRONZE WIRE FABRIC COATED COMPOSITES

Two-hundred mesh phosphor-bronze wire fabric was also studied. Discharge to these coatings resulted in extensive damage to the wire fabric, but no damage to boron or graphite composites. Damage to the fabric included total vaporization in areas near the discharge contact and other areas which appeared resin poor. Wire damage was extraordinarily directional as shown by the lines in Figure 38.

This same 200 by 200 mesh fabric was incapable of protecting high modulus composites from high amperage tests however. The graphite fiber reinforced composite (Panel No. 230, Figure 39) displayed some delamination and local resin charring after a 154 KA discharge. Most of the fabric was destroyed by the discharge. The boron fiber reinforced composite (Panel No. 231) was seriously damaged by a 170 KA discharge. The surface of the coating displayed several areas of arcing damage from the coating to the fiber. Additionally, the panel was warped from the point of strike contact to electrical ground. Since the radius of curvature was fairly constant, it can be concluded that all or nearly all of the fibers in this location were damaged. This was the only panel to display this behavior.

Finally, one extremely fine stainless steel fabric with 325 by 325 mesh and 1.4-mil diameter wire was tested as shown in Figure 40. The fabric was integrally bonded to the composites and provided complete coverage of one face of the laminate. The high amperage discharges to the panels punctured the fabric coating, caused severe delamination and cracking of the laminates. The poorly conducting steel did not perform well as a protective coating.

It is concluded from all of these tests that wire fabric coatings can provide excellent lightning protection to high modulus composites. Only highly conductive metals or their alloys work well, and weight considerations and costs restrict the choice of metal to aluminum. Other conductive metals are too dense or too expensive.

5.1.5 Knitted Wire Mesh

The success of aluminum wire fabrics in protecting high modulus composites from lightning discharge led to the study of knitted aluminum wire systems. The development of this concept focused on reducing weight and cost, and improving processability.

Knitted mesh has the added advantage of being quite flexible and offers the greatest ease of fabrication of the continuous coatings. The first material employed was a silver-plated brass knitted mesh, with 0.0035 inch diameter wire and 12 to 15 openings per inch. The open space was about 95 percent of the covered area. The wire mesh was bonded to the panels with a tape adhesive. The boron panel (No. 194) utilized the tape adhesive as an overlay while the graphite panel (No. 193) utilized it as an underlay. In both cases, resin flow embedded nearly all the wire fabric in resin; however, more wire protruded at the surface of the graphite panel. Following simulated lightning discharges

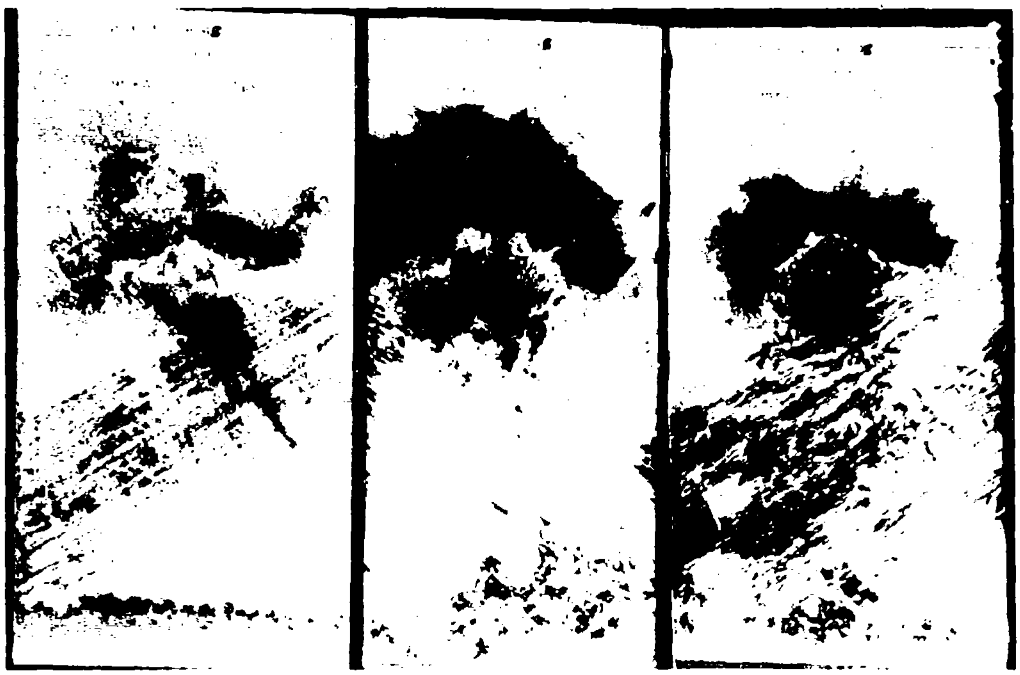


Figure 38: SIMULATED LIGHTNING DAMAGE TO FINE BRONZE WIRE FABRIC COATED COMPOSITE

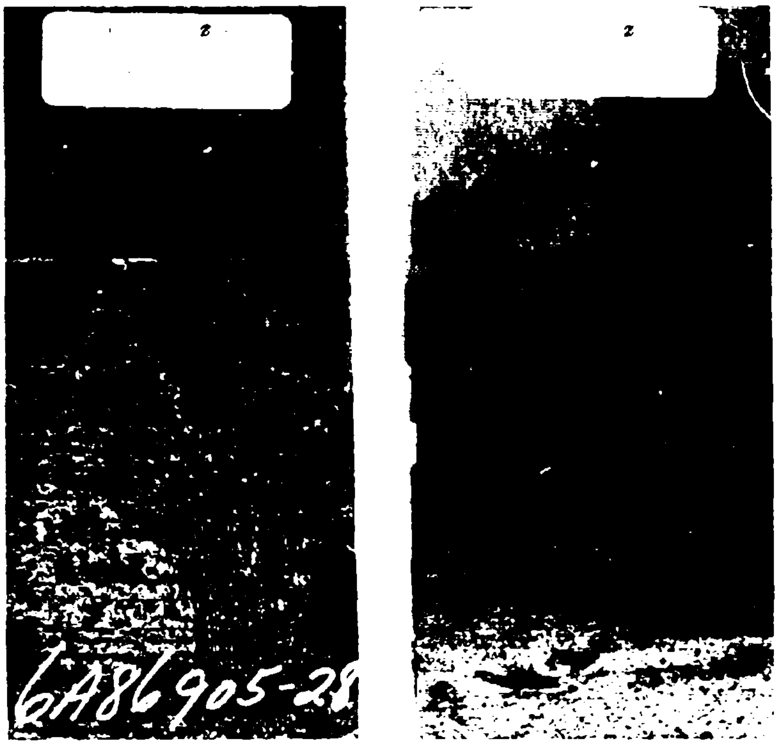


Figure 39: SIMULATED LIGHTNING DISCHARGE DAMAGE TO FINE BRONZE WIRE FABRIC COATED COMPOSITES

Figure 40 SIMULATED LIGHTNING DISCHARGE DAMAGE TO STAINLESS STEEL FABRIC COATED COMPOSITES

damage to the wire mesh was severe, but no structural damage to the reinforced composites could be discerned (Figure 41). The damage to the panels is less severe than it appears in the photograph. The success of this system led to the investigation of other coatings which utilize an aluminum wire. Aluminum is chosen due to its conductivity/weight ratio and the damage to the silver-plated brass coating was at least in part due to the higher electrical resistance of brass. Initial investigations focused on varying wire diameter at constant mesh density. These studies were followed by a series which investigated the effects of mesh density. This resulted in the advancement of a knitted wire coating to the Phase III testing sequence.

A 5 by 9 mesh coating was investigated with different aluminum wire diameters. The heaviest wire was 10 mils in diameter. This combination provided the same density of metal on the composite surface as the 200 by 200 mesh woven aluminum. This mesh coating offered some protection to both boron and graphite composites as shown in Figure 42 (Panel 212, 213). Evidence of surface flashover and resin scorching at the surface was observed.

When the wire diameter was reduced to 8 mils, very comparable results were obtained for the boron composite panel (Panel 210, Figure 43). The resin displayed the expected increase in degree of scorching. The graphite composite (Panel 208, Figure 43) utilized a 1 mil thick Kapton film undercoat. The panel was not delaminated and no damage could be detected.

Slightly finer fabrics employing 6-mil diameter wires were found successful in protecting boron composites (Panel 211, 216, Figure 44) but were unsuccessful in protecting graphite composites (Panel 214, 215) even though Kapton film underlayers were provided. Additional tests with other mesh sizes and underlayers merely confirmed these results.

Finer meshes were studied using 4-mil diameter wires. A total of 13 tests to 12 panels found metal density to be the most important parameter for lightning protection purpose. These 12 panels are 207, 209, 218, 219, 220, 221, 222, 223, 224, 227, 236 and 237. All of the 4 mil diameter wire meshes provided good protection to boron reinforced laminates at moderate discharges, but failed at high discharge (ca 175 KA) levels. Even at this level, the punctures were small and surface flashover patterns were evident. Protection of graphite composites by these fabrics was not as good. The panels displayed surface burns by moderate discharge levels and 1-inch by 2-inch delaminated outer plies by high discharge levels. Kapton film provided little additional protection to these laminates.

In summary, a very coarse knitted mesh can offer good lightning protection to graphite reinforced epoxy laminates provided a sufficiently large wire diameter is used. These coatings provide good protection to boron reinforced composites, providing a means for surface flashover to dissipate the lightning currents. Metal density per unit surface area

Figure 41 [illegible] DAMAGE TO [illegible] MESH COATED COMPOSITES

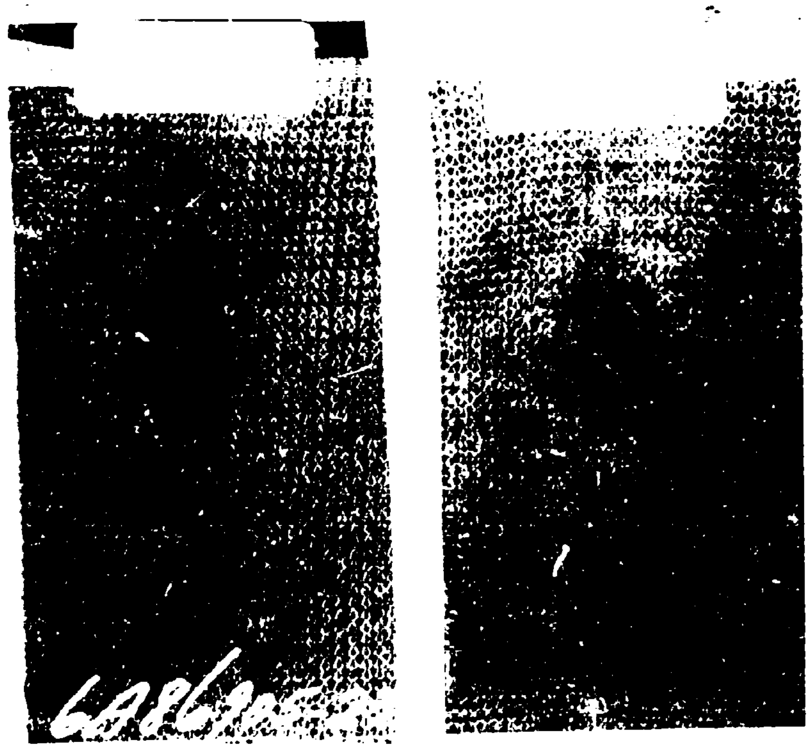


Figure 42 SIMULATED LIGHTNING DISCHARGE DAMAGE TO KNITTED ALUMINUM WIRE MESH COATED COMPOSITE LAMINATES

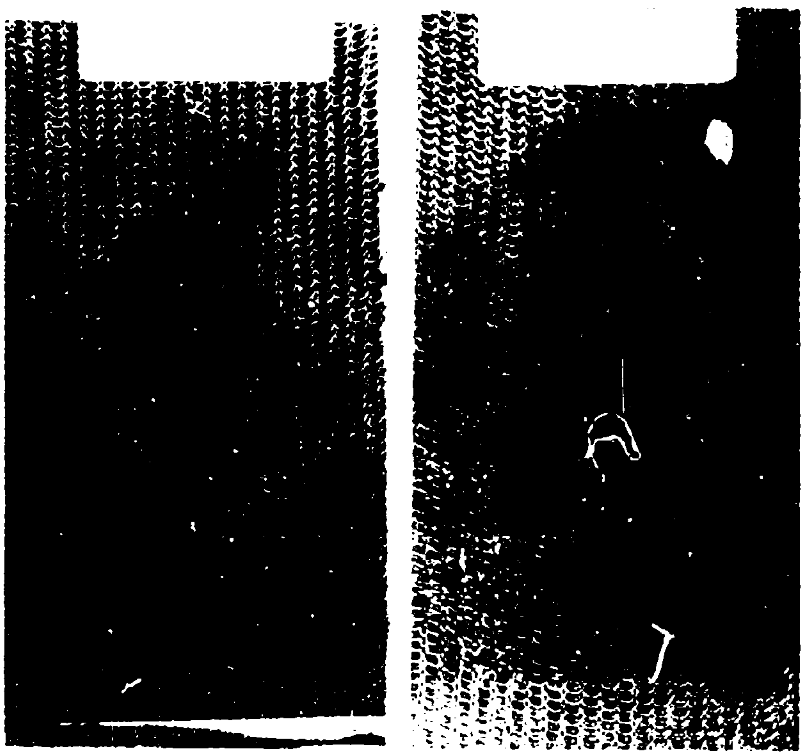


Figure 43. SIMULATED LIGHTNING DISCHARGE DAMAGE TO KNITTED ALUMINUM WIRE MESH COATED COMPOSITE LAMINATES

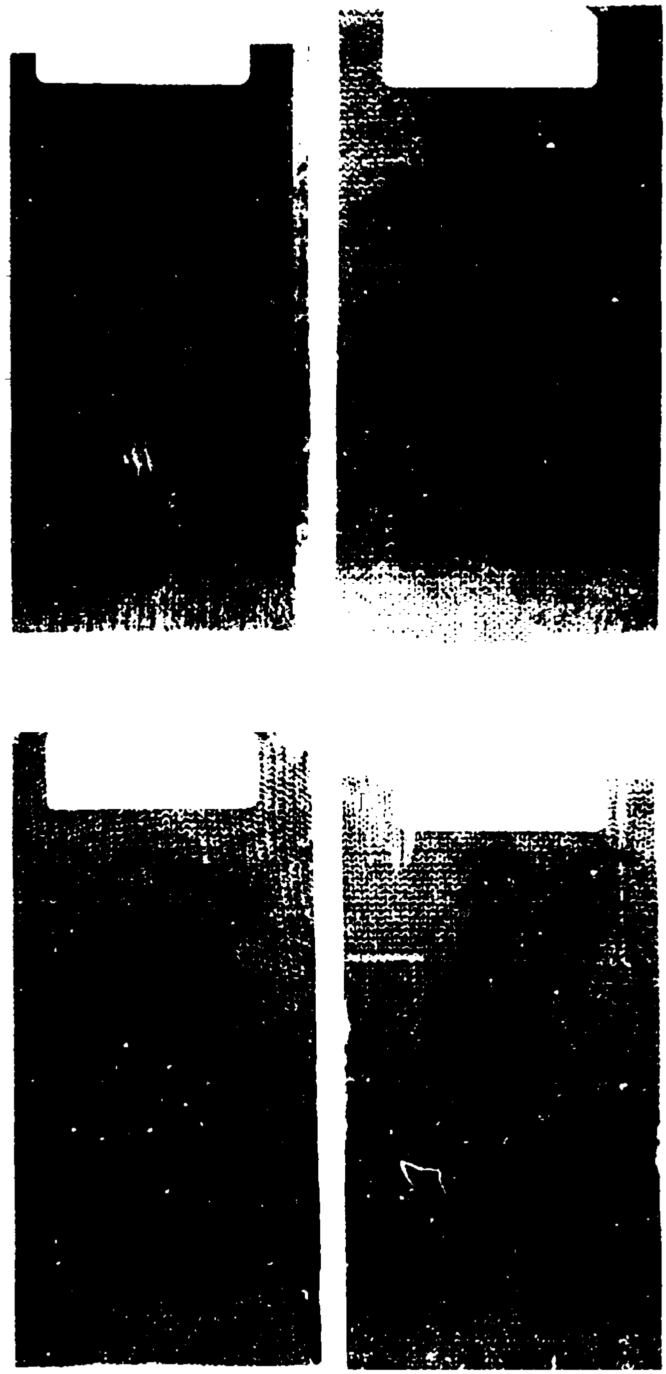


Figure 44 DAMAGE [illegible] COATED BORON EPOXY [illegible]

is the prime factor in determining the lightning protection offered by knitted mesh. For the same metal density, finer fabrics are preferred.

5.1.6 Plasma and Flame Sprayed Aluminum Coatings

Surface coatings of flame sprayed aluminum were very effective in preventing damage to boron composite panels for 100 KA discharges (Panel 029, Figure 45). The 4 mil coating showed discoloration and some cracking in the immediate vicinity of the probe, but no other damage. A 160 kiloampere oscillatory discharge caused extensive damage to the coated panel (Panel 030, Figure 45).

Plasma sprayed aluminum displayed quite a different protective behavior. Two and six mil plasma sprayed coatings on boron substrates (Panel 072, 073, Figure 46) were vaporized at the contact zone, much like the aluminum foil. In addition, the 2-mil coating was severely cracked. Plasma sprayed aluminum provides a less effective protection of graphite composites (Panel 068, 074, Figure 46). In this case, the panels with 2 and 5-mil coatings were severely cracked and evidence of current conduction by the fibers is present. The damage to Panel 068 is somewhat ambiguous as the outer plies of the graphite were burned during the plasma spray process. Consequently, this coating presented a worst case configuration to the discharge. The plasma spray coating on the panel was severely cracked along the two fiber axes and there was significant puncture damage on the back side of the substrate.

5.1.7 Metal Pigmented Paint

Epoxy, urethane and silicone paints have been pigmented with different metals, e.g., silver, copper, and aluminum, to form several coating systems. Of these metals, silver is the only effective particulate conductor.

Three mil silver epoxy paints were too thin to provide an effective coating. This is shown in Panel 091, Figure 47. There is considerable evidence of surface flashover, especially to the outer edges of the panel. Current was conducted into the boron fibers, however, as shown by the series of small puncture holes across the substrate. Systems utilizing this same silver pigmented epoxy over a conductive inner layer were also ineffective. Pyralin cloth with a 20 ohm/square resistance was integrally bonded to the panels and then painted with 2 to 4 mils of silver paint. Damage to the fiber glass control panel (Panel 065, Figure 47) was limited to a small burn spot in the paint and residual markings due to a surface flashover. Interestingly, the surface flashover occurred first to the outer panel edges and then to ground. This same coating system was ineffective in preventing puncture of either boron (Panel 092) or graphite (Panel 090) laminates (Figure 47). Surface flashover was promoted, as evidenced by the surface markings, although considerable current loads were carried by the fibers.

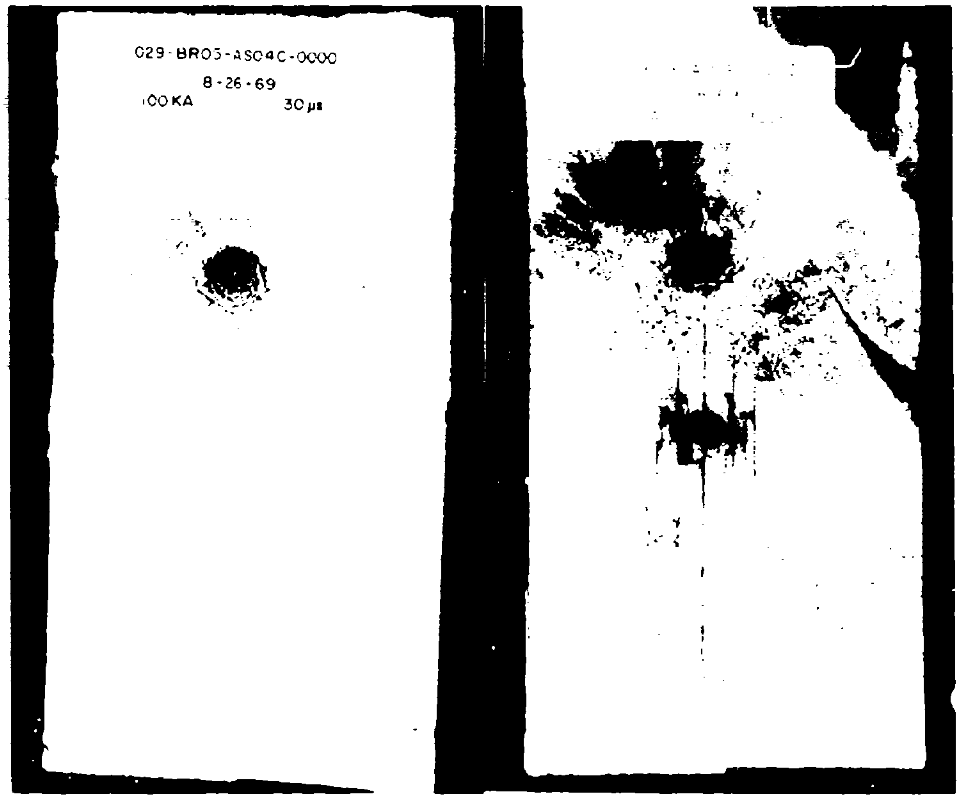


Figure 45: DAMAGE TO FLAME-SPRAYED ALUMINUM COATED COMPOSITE LAMINATES

Figure 46. DAMAGE TO PLASMA-SPRAYED ALUMINUM COATED BORON EPOXY AND GRAPHITE EPOXY COMPOSITES

Figure 47 DAMAGE TO SILVER PIGMENTED EPOXY COATINGS

Silver pigmented epoxies were also applied to composite panels by spraying and the panel edges were covered with a 3-mil thick, 1-inch wide aluminum tape. Discharge to the boron panel (Panel No. 103, Figure 48) resulted in a very slight surface discoloration and destruction of the tape. The paint surface was neither cracked nor pitted but was covered with a light yellow-brown film. The aluminum strips were blown from the panel edges but left much of the adhesive behind. The current apparently arced between the two aluminum strips. This is shown by the aluminum deposits across the face of the panel.

The same coating system was less successful in protecting graphite composites (Panel No. 102, Figure 48). The paint was cracked or chipped away in a large area and fiber conduction was apparent. Damage to the aluminum strips was primarily due to electromagnetic forces and portions of the strips were torn from the panel. The aluminum between the discharge area and ground was less disturbed than that on the boron panel as shown in Figure 48. This points out the difference in the success of the same coating on the different substrates. The discharge to the boron panel was dissipated by surface flashover and remained external to the composite while the discharge to the graphite panel traveled through the coating as well as the fibers. The more numerous graphite fibers as well as graphite's inherent conductive properties make graphite composites less resistant to current penetration than their boron counterparts. It is also important to note that boron composites have the additional insulative property of the boron sheath which surrounds the conductive core of the fibers.

A silver pigmented epoxy coating was also applied in the form of preimpregnated 181E style glass fabric. The fabric was directly bonded to the test panels (Panel No. 121 and 122) during cure and formed an integral part of the laminate. (The fabric was of limited supply and the 5-inch by 10-inch pieces did not completely cover the 6 inch by 12 inch test panels). Discharge damage to the boron composite (Figure 48, Panel No. 122) resulted in extreme discoloration of the coating, some resin burning at contact and a series of cracks between the stroke attachment point and ground. A small back side puncture was the only visible damage to the panel. It is believed this puncture was caused by impact with the discharge probe and not to the discharge current. In contrast, the graphite panel (Figure 48, Panel No. 121) was blackened about the stroke attachment point, but not between this point and ground. The epoxy matrix was cracked. The coating fabric was extensively delaminated from the graphite matrix and might be an indication of graphite fiber conductions. This coating system appears to be an improvement over the simple silver-epoxy paint system.

Conventional aluminum and copper filled paints provided excellent lightning protection for the glass reinforced test panels but poor protection for high modulus composites. These paints provide surface flashover due to their electrical properties; the arc will remain exterior to a panel unless it is guided into or through the substrate by conducting

Figure 48 SIMULATED LIGHTNING DISCHARGE DAMAGE TO SILVER PIGMENTED EPOXY COATED COMPOSITES

materials. Lightning discharge arcs are guided into the high modulus composites by the low resistance of the fibers themselves. Painted panels frequently give the appearance of being more damaged than unpainted panels. The vaporization of the resins causes bubbling of the paint and can explosively remove much of it from the surface. In addition, the paint is often scorched. These effects are shown in Figure 49, which compares the damage to boron, graphite and glass reinforced panels coated with 5 mils of an aluminum pigmented polyurethane paint. Copper filled polyurethane and aluminum filled silicone base paints displayed much the same damage. The use of peripheral aluminum foil strips in conjunction with these paints gave no lessening of the graphite damage and increased the damage to the boron laminates.

Undercoatings of carbon filled Pyralin cloth were also ineffective. The cloth was severely ripped and was debonded from the surface while the substrate was punctured. The use of a conductive inner layer was deleterious in this case. These results are shown in Figure 50, Panel 083 and 084.

Kapton film sandwiched between the two outer fiber plies provided no improvement to the panels coated with aluminum pigmented polyurethane paints. In fact, severe damage to the boron (Panel 079, Figure 50) occurred by explosive rupture of nearly all the outer ply boron filaments. A similar graphite panel was punctured and delaminated at the discharge contact zone and at the ground connection. These results are shown in Figure 50.

The exceedingly poor results with these conventional paints prompted several formulation modifications. These were designed to investigate the effects of other pigment shapes (the paints described above utilized flat, "leafing" pigments) as well as the pigment volume concentration or PVC. The polyurethane paints previously discussed had pigment volume concentrations of 12%.

An aluminum pigmented epoxy (29 percent aluminum by volume) provided excellent protection to a glass reinforced control panel, but little or no protection to boron or graphite reinforced structure (Figure 51, Panel No. 112, 113 and 114). The boron panel was pitted and cracked along its 6-inch dimension, with many small areas of delamination on the back side. Surface markings on the coating indicated that some surface flashover occurred. These markings consist of blackened areas and cracked "rings" (Figure 51). Rings of this type have also been observed on silver pigmented coatings. The graphite panel displayed extensive delamination at the stroke contact, a large 1-inch by 2-inch hole on the back side, complete resin burnoff in some areas and delamination across the full width of the panel at ground. The damage to the panel was quite extensive.

Two copper filled systems met with even less success. The first utilized a 29 percent PVC of a 1 micron copper powder in an epoxy matrix. Protection for the glass reinforced panel was excellent, the coating displaying minor discoloration and "tracking." The boron panel was severely

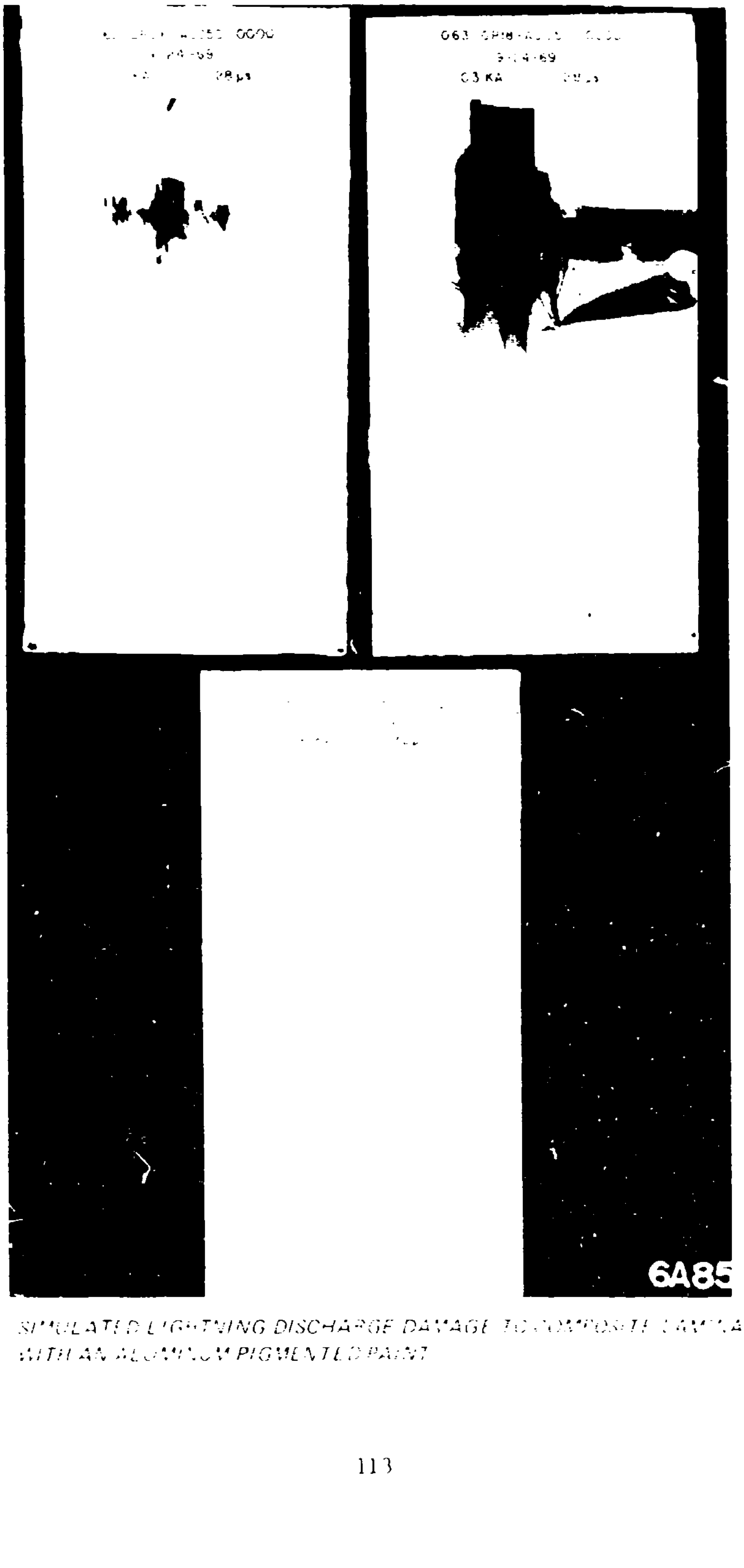


Figure 49 SIMULATED LIGHTNING DISCHARGE DAMAGE TO COMPOSITE LAMINATES COATED WITH AN ALUMINUM PIGMENTED PAINT

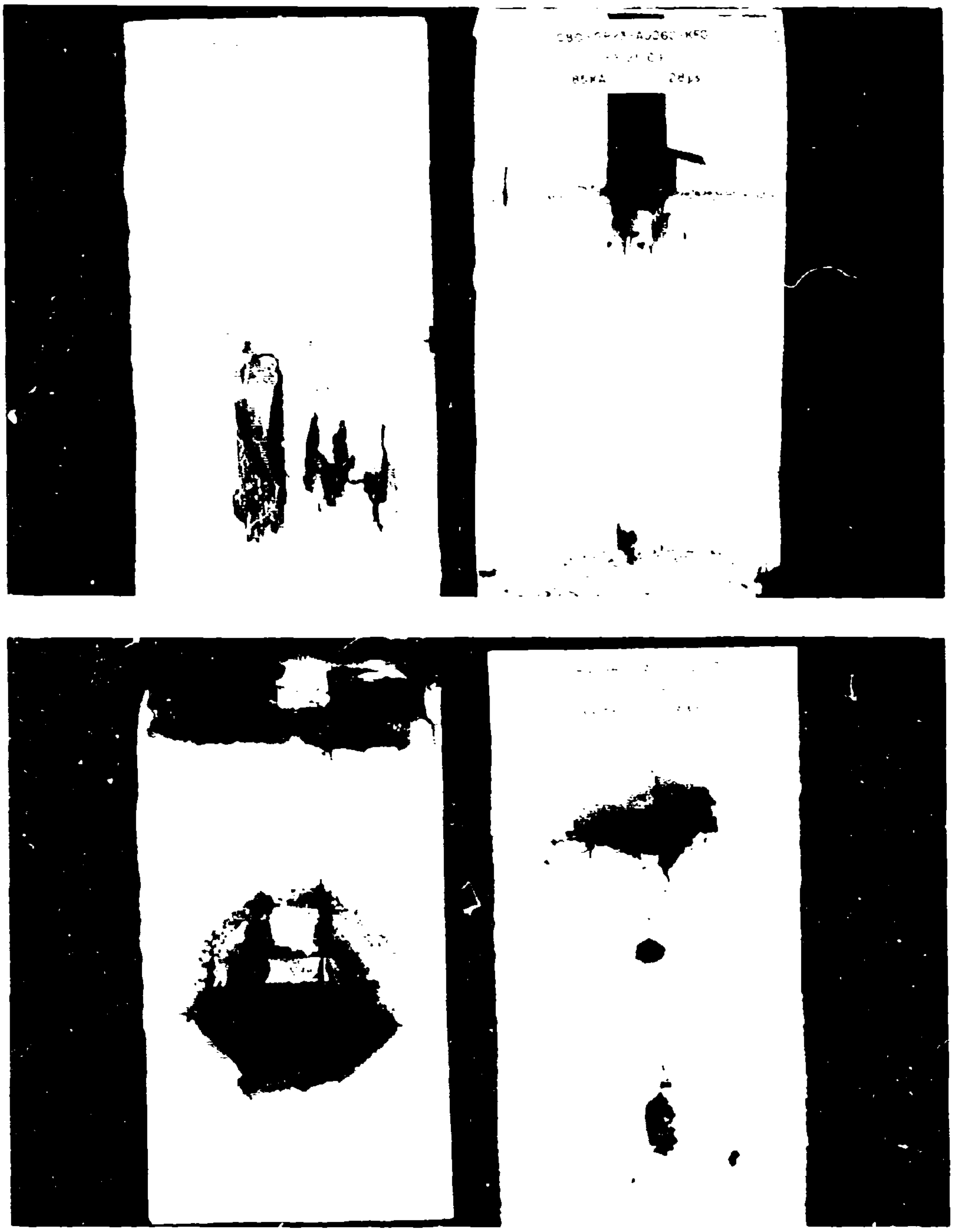


Figure 50 SIMULATED LIGHTNING DISCHARGE DAMAGE TO HIGH MODULUS COMPOSITES COATED WITH ALUMINUM PIGMENTED PAINTS

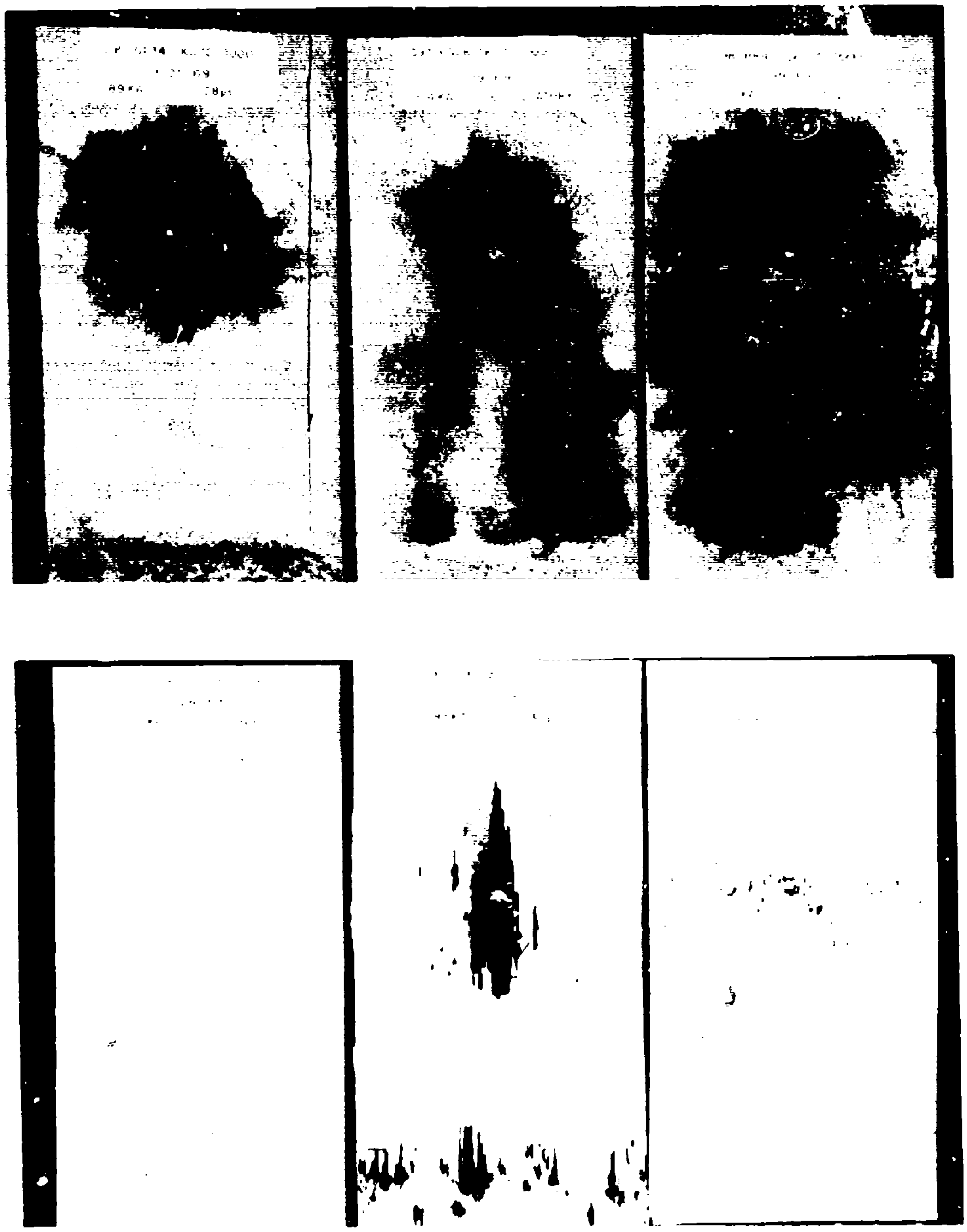


Figure 51: SIMULATED LIGHTNING DISCHARGE DAMAGE TO COMPOSITE LAMINATES COATED WITH COPPER AND ALUMINUM PIGMENTED PAINTS

ruptured across the 6-inch width with the exploded boron fibers displaying their tungsten core. Fiber conduction also burned the coating between the contact and ground, while the back side displayed a scorched epoxy composite matrix. The graphite panel displayed a 6-inch long delamination across the face, a large hole and considerable delamination and shattering at the ground connection. The absence of any discoloration or burning of the coating indicates the current was primarily carried by the fibers.

The second copper coating used a silicone matrix. This was also utilized a PVC of 29 percent. This powder was of unknown mesh, but larger in size than the powder utilized above. The glass reinforced control panel (Panel No. 097, Figure 51) displayed two large burn tracks from the contact to ground. Portions of the coating in these areas were burned and peeled away from the primer. The boron panel (Panel No. 098) was completely severed across the 6-inch dimension. The crack appears to be the result of a series of small, closely spaced holes in the panel. Evidence of the initiation of another crack 2 inches closer to ground is given by a group of small holes. Nearer ground, the panel displays a clean 3-inch long crack. It is to be noted that damage orthogonal to the contact-ground line is common and most frequent with boron composites. The coating surface of this panel was discolored also.

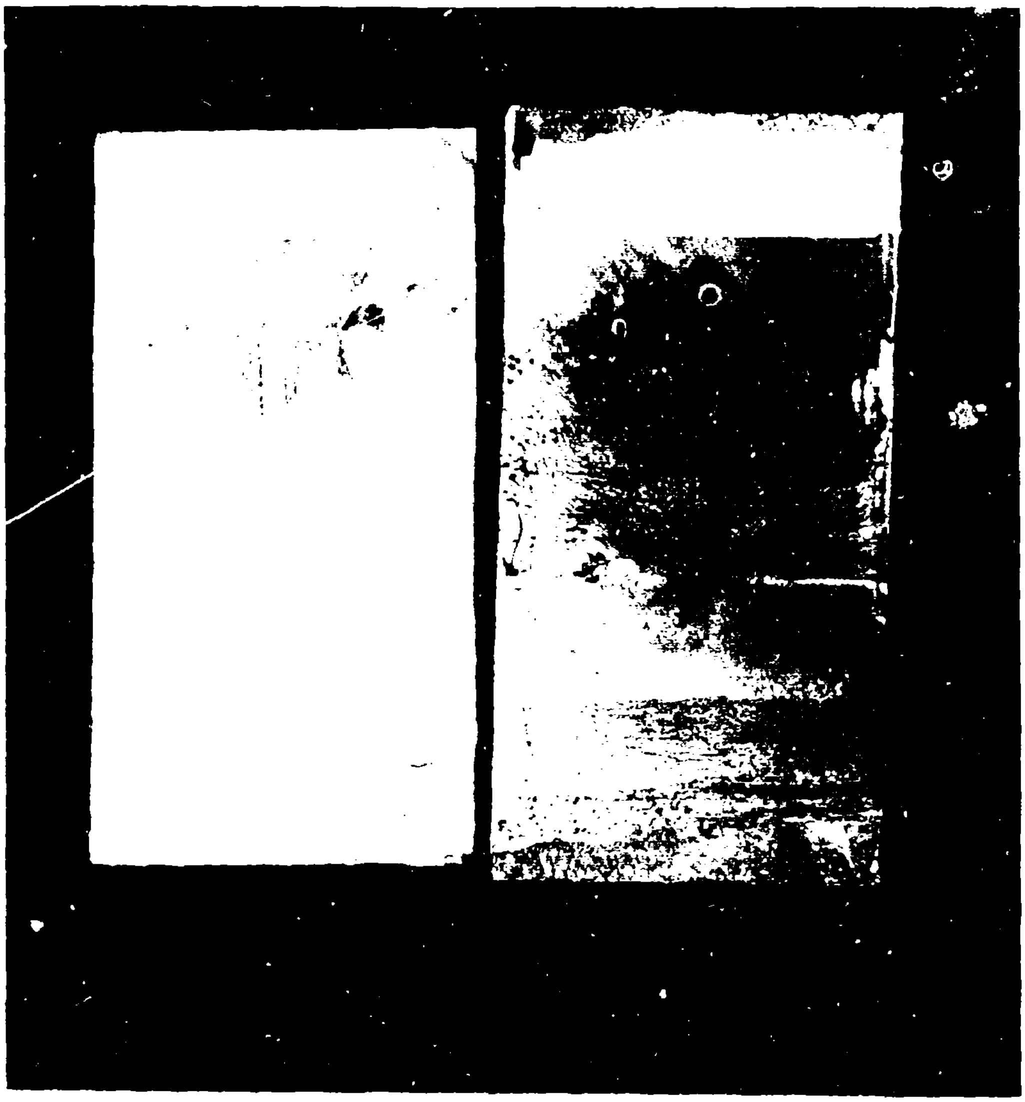
The graphite reinforced panel (Panel No. 108) displayed a 3-inch by 3-inch area which was grossly delaminated and in which most of the resin matrix had been burned away. A large back side crack and burned area at ground was also visible.

These results show that aluminum and copper pigments dispersed uniformly throughout a coating do not develop sufficient conductivity to provide lightning protection to boron filament or graphite fiber reinforced composites. Even at metal volume concentrations as high as 29 percent, these coatings are not conductive. This is presumably due to the nonconductive surface layers of the copper and aluminum pigments. Such nonconductive layers are formed by the reaction of the metal with oxygen in the atmosphere to form a thin oxide coating.

The development of aluminum or copper paints as conductive systems relies upon protecting the metal from oxidation. A copper pigmented epoxy which had been specially treated to prevent surface oxide formation was found to provide a conductive coating. This system was effective in preventing lightning puncture of boron and graphite panels. Figure 52 shows the damage to panels coated to a thickness of 10 to 14 mils. The coating was very inefficient when compared with aluminum foil or silver paints, and suffered extreme cracking and pitting. The copper coating was also broken away at the ground terminal. This paint was more porous than the silver filled epoxies and was applied as a paste.

5.1.8 Metal-Sandwich Coatings

Metal-sandwich coatings are prepared by depositing a metal slurry over a primed surface. As the solvents are flashed off, the metal is



[illegible] SIMULATED LIGHTNING DISCHARGE DAMAGE [illegible]
BORON EPOXY AND GRAPHITE [illegible]

concentrated in a thin layer. A finish coat of clear epoxy serves as the top coat and binder. Cross sections of the coatings display some porosity in the metal layer but the sandwich nature is obvious. This coating system assures maximum particle-to-particle contact and a multiplicity of conductive paths in all directions. Such coatings were prepared from aluminum and copper powders, and actual powder thickness in these coatings was estimated to be 5 mils.

The aluminum sandwich coating was severely damaged in all cases (Figure 53, Panel No. 126, 131 and 132). The fiberglas control panel was pitted and a 1-inch wide track resulted from the stroke attachment to ground. No fiberglas damage was observed. The boron panel was cracked along nearly the entire 12-inch length. At the attachment and at ground, the coating was peeled from the panel and several holes were observed at the attachment and ground areas. The graphite reinforced panel was completely shattered at the ground connection and also at a point halfway between the stroke attachment and ground. At the arc attachment, a 1 square inch hole in the panel with excessive back side delamination was observed. Much of the sandwich coating was blown or peeled away from the substrate surface.

Copper sandwich coatings provided comparable results to those outlined above, except that a larger area of the graphite panel was destroyed (Figure 53, Panel No. 128 and 129). The copper sandwich coating was greatly improved when applied over a 3-mil Kapton film (Figure 53, Panel No. 130). The arc apparently flashed to the panel edge and then to the graphite fibers on the back side. Damage was limited to the composite edges. Presumably, the use of metal diverter strips can rectify this situation and improve the protective qualities of these coatings.

One interesting phenomenon was found when the copper sandwich coating was tested on a fiberglas substrate. A discharge of a 25 KV charged capacitor bank could not be initiated to this panel (Panel No. 127); however, radially discharged multi-finger streamers were observed and lasted for approximately 10 minutes as the capacitor voltage dropped to 15 KV. The whole coating surface was pitted (Figure 54).

5.1.9 Other Paint Systems

Sterling MTNS carbon black was prepared as a 40 percent by volume pigment in Araldite 488E32 thermoplastic epoxy. This coating provided no protection to either boron or graphite reinforced panels. Both composites were punctured and severely delaminated by the discharge. When aluminum powder was added to the coating system, no reduction in damage to the panels was observed and a greater amount of damage to the coating occurred (Figure 55, Panel No. 139, 144 and 147). In these tests, the boron panel was completely fractured across its 6-inch dimension near the ground location.

This same carbon black/aluminum filled system was also applied over a 6-mil dielectric undercoating. The dielectric coating consisted of 45 percent boron nitride dispersed in Araldite 488E32. The damage to the

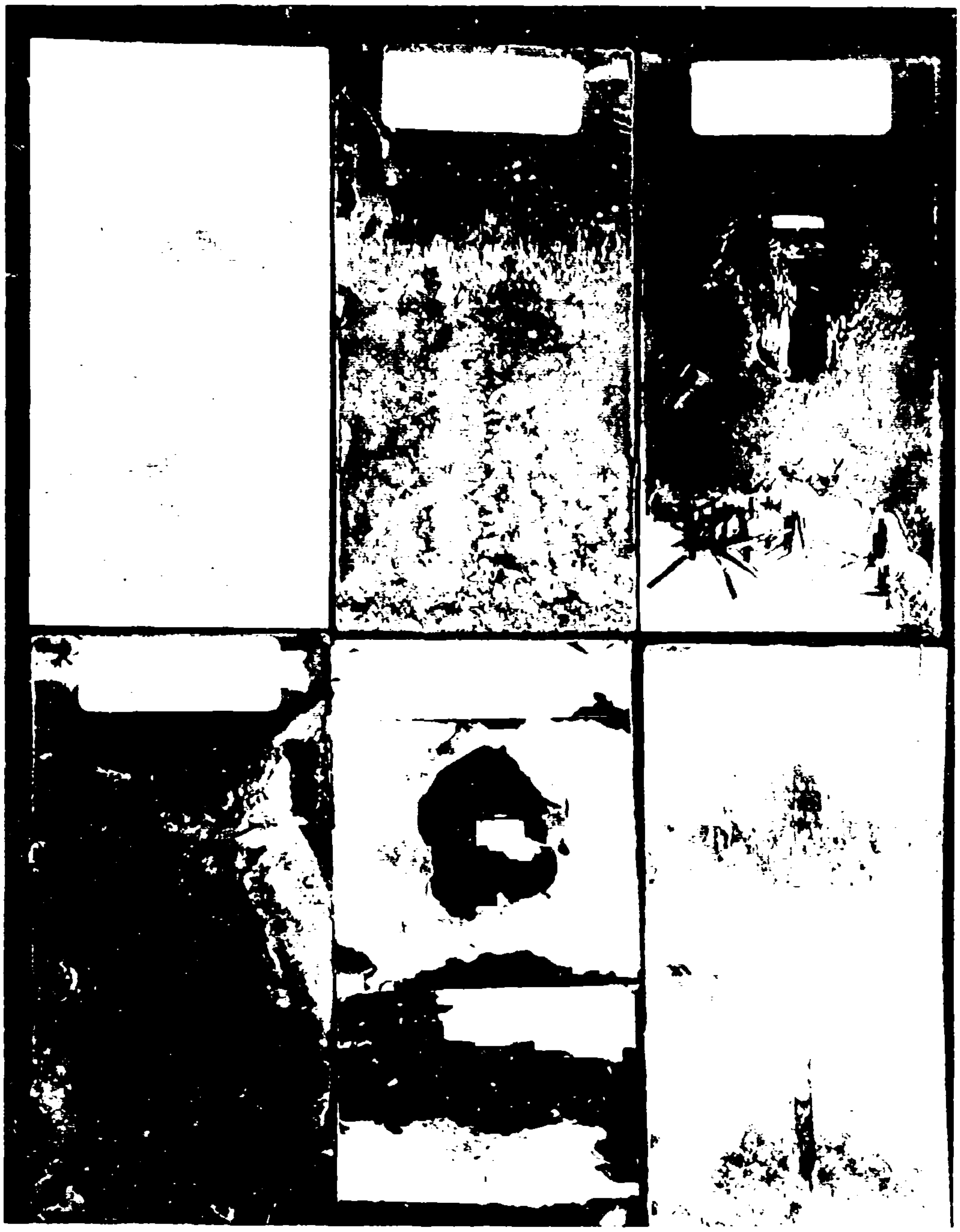


Figure 53 SIMULATED LIGHTNING DISCHARGE DAMAGE TO COMPOSITE LAMINATED COATED WITH ALUMINUM AND COPPER SANDWICH COATINGS

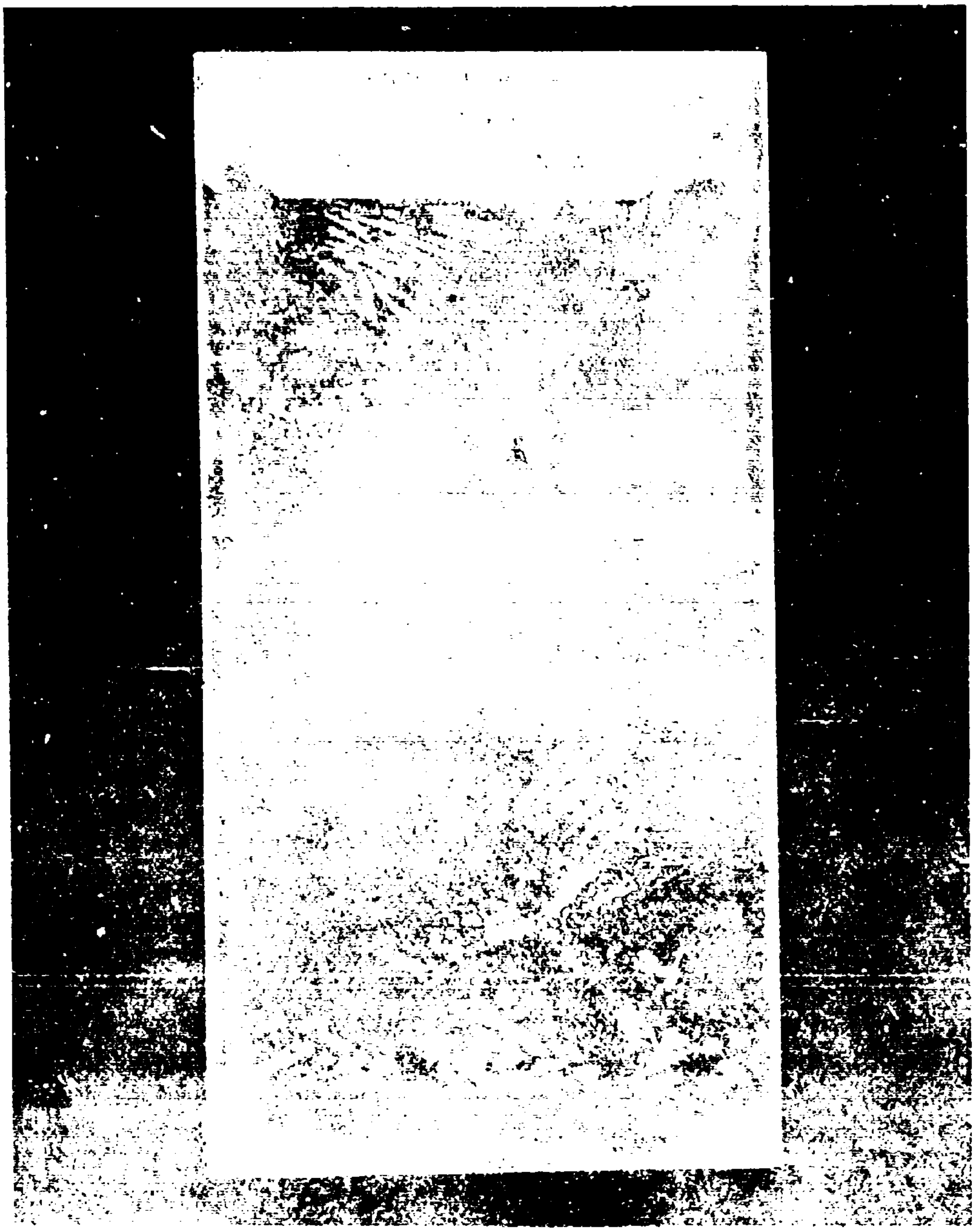


Figure 64 GLASS FABRIC REINFORCED LAMINATE COATED WITH A COPPER SANDWICH COATING

panels was not reduced (Figure 55. Panel No. 140, 145 and 149). The fiberglas panel received only surface markings; the graphite panel was punctured, delaminated and the matrix was burned away; and the boron panel was completely severed at the contact zone and scorched from that point to ground.

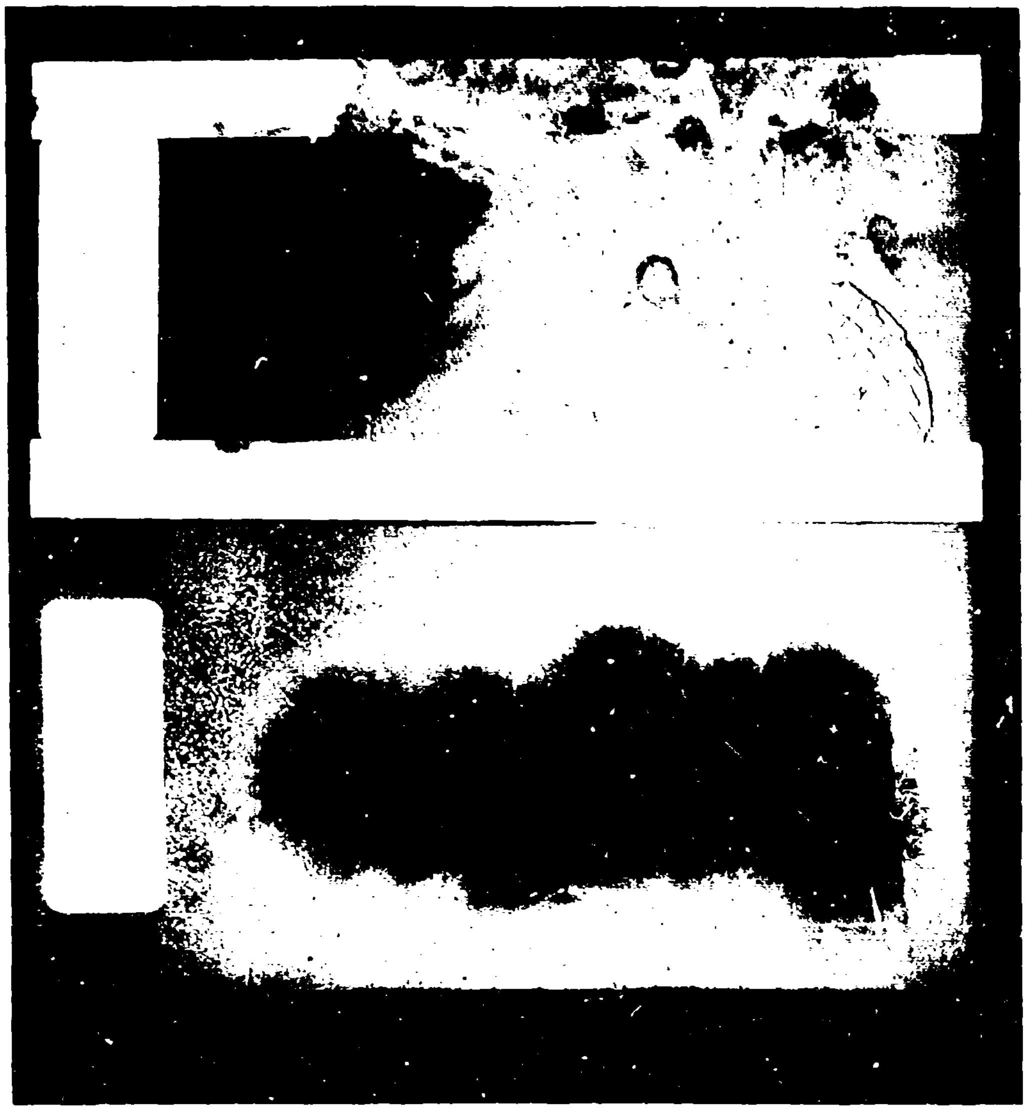
Epoxy paints pigmented with the highly conductive Cabot Vulcan XC-72 Grade Black were tested in a variety of coating configurations. A 5-mil thick coating very successfully protected a glass reinforced epoxy panel (No. 159), as shown in Figure 56. Surface flashover left a gray, smoke colored track across the panel surface, but no damage to the coating or the substrate was observed. The same coating was completely unsuccessful in protecting boron or graphite reinforced composite panels (No. 155 and 170), as shown in Figure 57. Both laminates were punctured by the discharge and no evidence of surface flashover was visible. The surface of the coating on the graphite composite displayed many small bubbles due to resistance heating of the fibers.

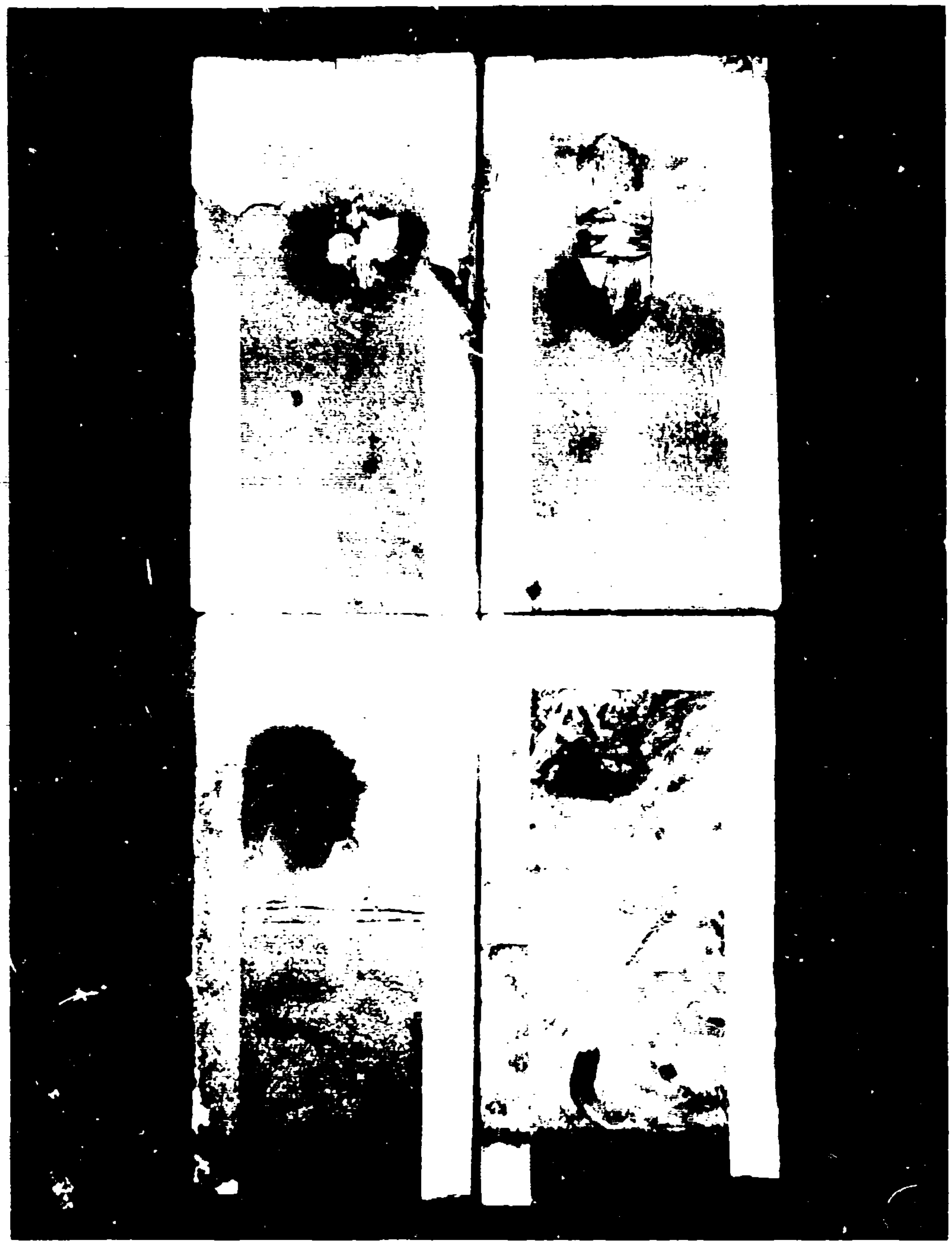
The addition of expendable aluminum strips along the panel edges did little to improve the protective qualities of this coating system. One inch wide, 3-mil thick aluminum was bonded over the coated surface along the two 12-inch panel sides. Damage to the panels was comparable to that observed in the absence of the strips. Little distortion of the aluminum occurred and it can be concluded that the aluminum did little to promote surface flashover. The glass reinforced control panel (No. 162, Figure 56) for this coating concept was discolored by the surface flashover and subsequent vaporization of the aluminum.

The potential of polyimide insulating layers with carbon black pigmented paints was also studied. One mil thick Kapton film was integrally bonded to the outer composite surface (Panel No. 156, 168). The carbon black pigmented coating was then applied over the Kapton. Discharge to this series of panels resulted in panel puncture and no reduction in structural damage. This same system was tested with expendable aluminum strips along the panel edges (Panel No. 157, 158). Again, the discharge punctured the panel and no evidence of surface flashover to the aluminum was apparent. These results are shown in Figure 57 and 58.

A successful coating combination was found when the Kapton film thickness was increased to 3-mils. This film was also integrally bonded to the composite surfaces and expendable aluminum strips were provided along the panel's 12-inch dimension side (Panel No. 181, 182). The test results in Figure 58 show the protective capability of the 1 and 3 mil thick Kapton insulative layers. As shown in the figure, surface flashover for 100 KA discharges is very apparent; the expendable strips are largely destroyed and the panel face is covered with a smoky deposit. The success of this coating is undoubtedly due to the additional insulating properties of Kapton film.

The dielectric strength of 1-mil Kapton polyimide film at 25°C and 50 percent relative humidity is reported to be 7000 volts, while that of





[illegible] SIMULATED LIGHTNING DISCHARGE DAMAGE TO CONDUCTIVE BLACK KAPTON FILM COATED BORON EPOXY AND GRAPHITE EPOXY LAMINATES

a 3 mil film is 13,800 volts (ASTM test method D-149-61). Undoubtedly, it is this increase in breakdown strength which determines the coating system's ability to protect the reinforced composites from simulated discharges because the dielectric film serves to prevent attachment of the lightning arc to the high modulus fibers and instead conducted the discharge current away by forming a surface flashover.

A conductive cloth coating concept was also tested. The conductive cloth, a carbon black pigmented polyimide impregnated glass fabric, had a resistance of 20 ohm/square. This material was integrally bonded to the composite. Expendable aluminum strips, each 1-inch wide and 3 mils thick, were provided along the long sides of the panel. Both boron fiber and graphite fiber reinforced laminates were punctured when a 90 KA discharge was directed toward these coatings. The distortion of the aluminum strips indicates the discharge currents were partially shunted into the metal. The conductive cloth was torn and peeled from the surface of the composites. It can be safely concluded that the 20 ohm/square resistivity is too high to drain lightning discharge currents away from the high modulus fibers. As previously discussed, the addition of 2 mils of a silver pigmented epoxy does not improve the performance of this coating.

Several inorganic salt filled coatings were studied. The first was prepared by adding aluminum trifluoride to Dow Corning DC 92-009 silicone. This system provided no protection to the panels but served as baseline for future coating development. Actual damage to both panels included punctures and panel delamination. The silicone system is the most flexible coating matrix investigated and displays excellent adherence to the composites.

Al_2F_6 was added to a carbon black epoxy system and applied over the boron nitride dielectric undercoating. This system was not successful in reducing the damage sustained by the boron and graphite reinforced composites (Figure 59, Panel No. 142, 146 and 148).

Another coating was prepared by sprinkling powdered lithium chloride over a wet carbon black epoxy coating. The final coating was 11 mils thick and the lithium chloride was bonded well to the surface. Discharges to these panels provided good evidence that it might be possible to utilize low boiling point salts as heat sinks (Figure 59, Panel No. 141, 143 and 150). Much of the coating was burned away from the panel surface and that which remained was extremely porous.

Epoxy paints pigmented with other types of inorganic salts were tested to further investigate the potential of salt pigmented coatings. The salt chosen for the initial series was potassium nitrate (KNO_3). This compound has a relatively low melting point (335°C) and decomposes above 400°C. This latter property might be considered important for a conductive coating when the potential decomposition products are ions or possess low ionization potentials.

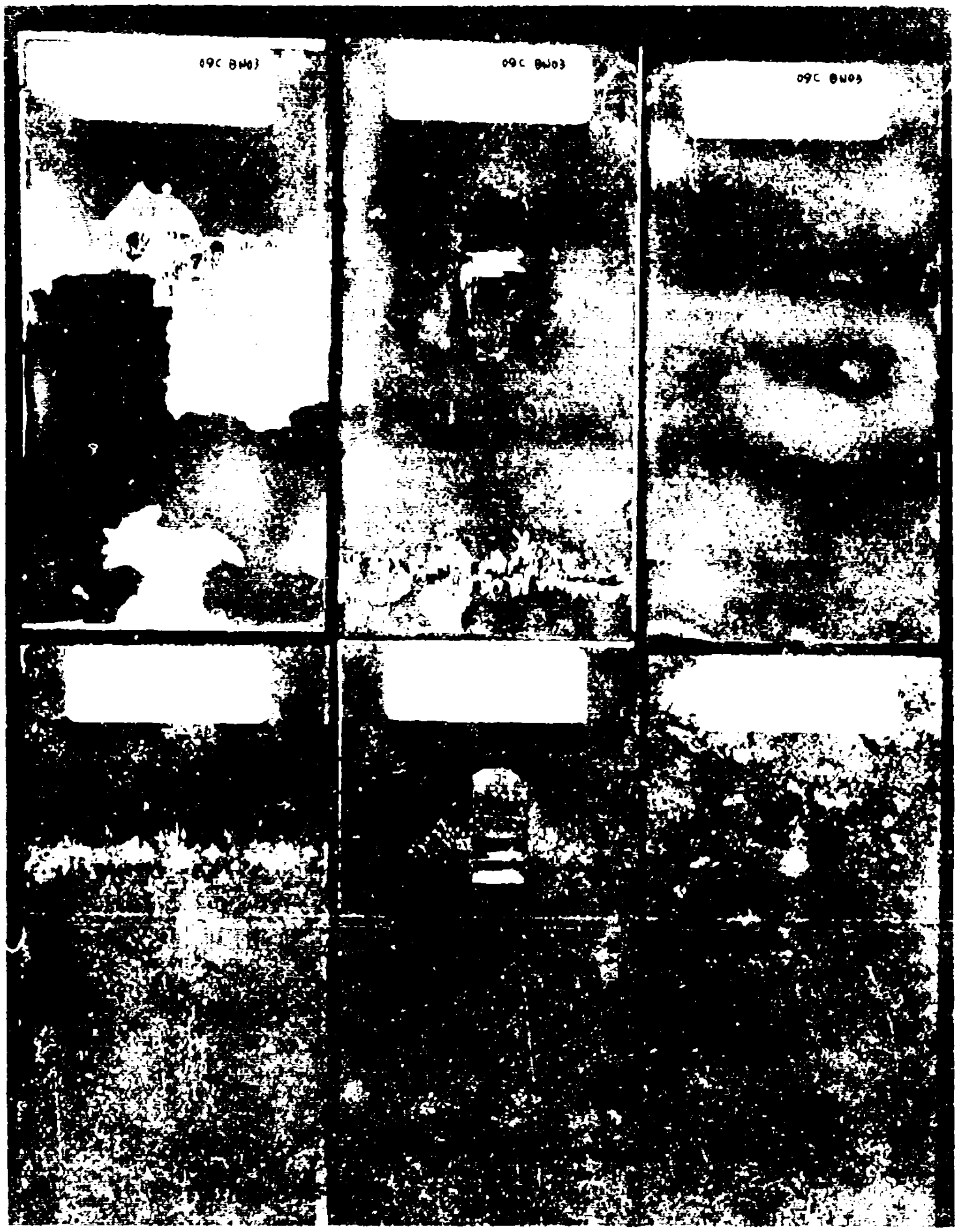


Figure 59 SIMULATED LIGHTNING DISCHARGE DAMAGE TO COMPOSITE LAMINATES COATED WITH INORGANIC SALT PIGMENTED PAINTS

A 10 mil epoxy coating containing 40 percent pigment volume concentration (PVC) of this salt was applied to boron and graphite composite panels with and without expendable aluminum diverter strips (Panel No. 163, 166, 171 and 175). As shown in Figure 60, 50 KA and 110 KA discharge to the boron panel resulted in panel damage and puncture; however, 94 KA discharge to graphite panels (No. 171) led to surface flashover to the laminate edge with subsequent conduction by the outer fibers. This is a surprising result, since all previous tests have indicated boron to be the easier fiber to protect; consequently, these results prompted several additional coating formulations. Panels were prepared with expendable aluminum strips along the outer edges and a 1-mil Kapton film undercoating (Panel No. 167, 174). One hundred KA tests revealed this to be a satisfactory coating system (Figure 61). It was also found that coated panels with diverter strips but without Kapton film undercoating were severely damaged (Figure 61, Panel No. 166 and 175).

A 6-mil boron nitride (BN) filled epoxy paint as an insulative layer did not prevent severe panel damage with or without diverter strips (Figure 62, Panel No. 160, 165, 172 and 173). In addition, the insulative coating was resin poor and displayed poor adhesion; the coating was badly cracked and peeled from the panel following the discharge test. This attempt to substitute a 40 percent PVC boron nitride pigmented epoxy for the Kapton film was unsuccessful.

When the potassium nitrate pigmented epoxy coating thickness was reduced to 5 mils it provided satisfactory lightning discharge protection to a boron reinforced composite panel, but no protection to a graphite counterpart (Figure 63, Panel No. 189 and 188). The latter panel was punctured by the discharge arc. When the coating thickness was 7 mils and the PVC reduced to 4 percent, a satisfactory system was again attained (Figure 63, Panel No. 190 and 191). The coating displayed very minor damage and surface flashover left the panel surface gray. This coating system, however, shows a high impedance since the capacitor bank had to charge to 21 KV and the discharge probe gap had to be reduced to 1/16 inch before the discharge would be initiated, while a normal discharge occurs at 15 to 18 KV with a gap of 1/4 inch.

Other coatings employing potassium sulfate (K_2SO_4) and magnesium nitrate ($Mg(NO_3)_2 \cdot 6H_2O$) were shown to provide comparable results. Since the potassium sulfate system possesses none of the properties originally thought necessary for a good coating system, an unfilled epoxy system was tested (Panel No. 201 and 202). Surprisingly, this provided good flashover characteristic and little damage to the coating. Discharge to glass reinforced controls coated with these same coatings could not be initiated.

In view of these results, it has been tentatively concluded that these coatings represent a poorly conducting surface which causes or contributes to surface flashover only if incorporated over a conductive composite. It is not fully understood why these systems are successful when similar coatings pigmented with conductive materials such as carbon black are not.

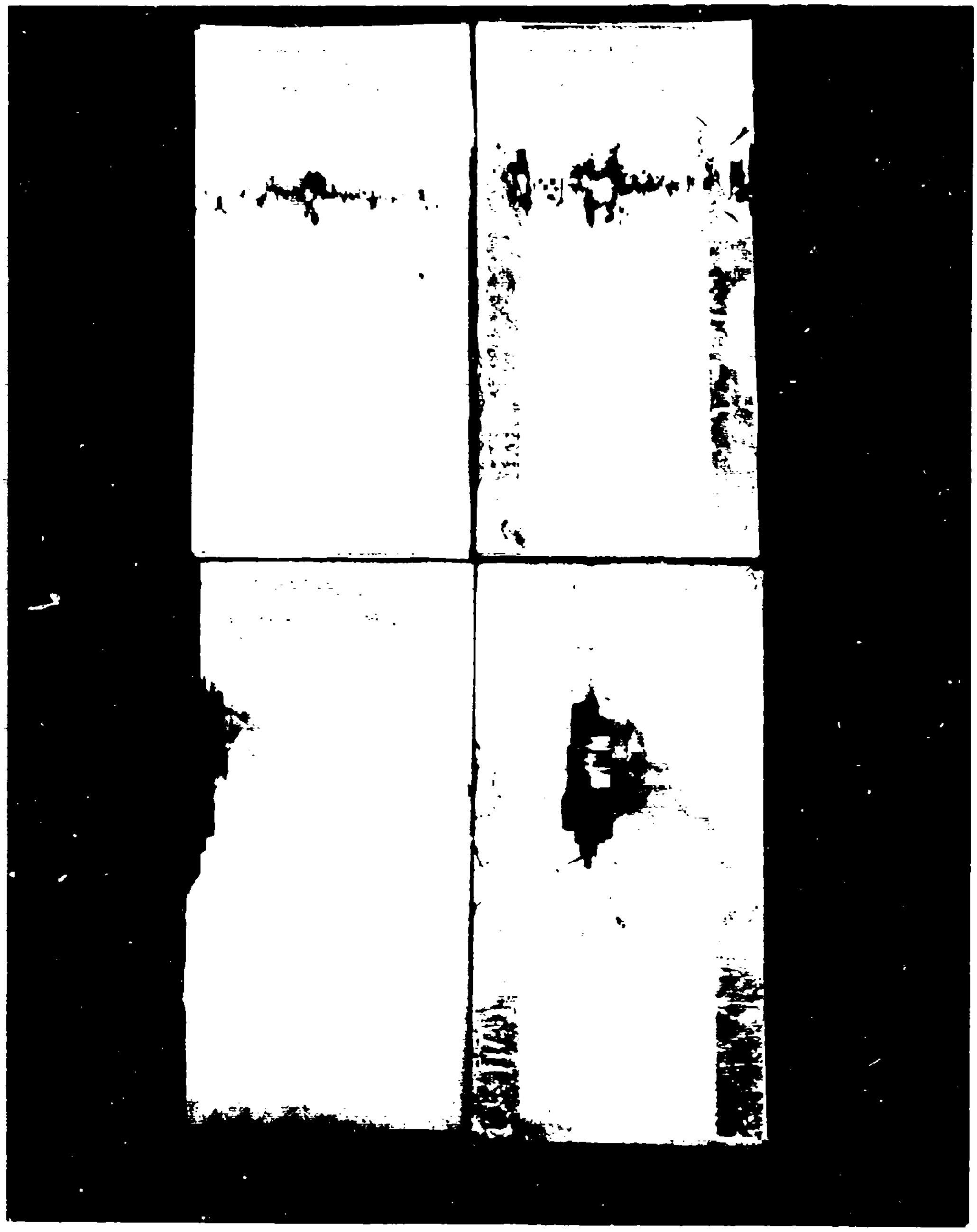
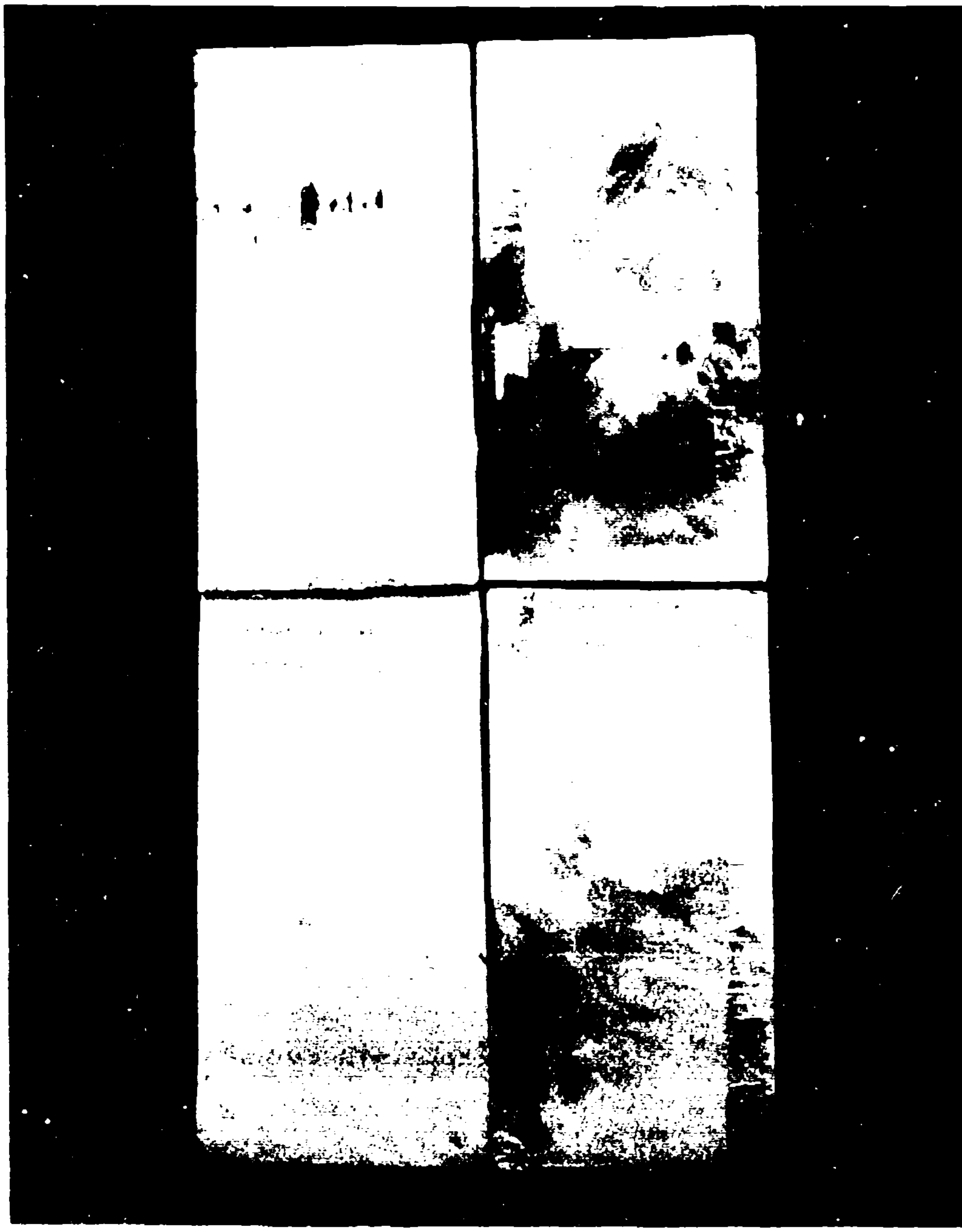


Figure [illegible] SIMULATED LIGHTNING DISCHARGE DAMAGE TO LAMINATES PAINTED WITH INORGANIC PIGMENTED COATINGS



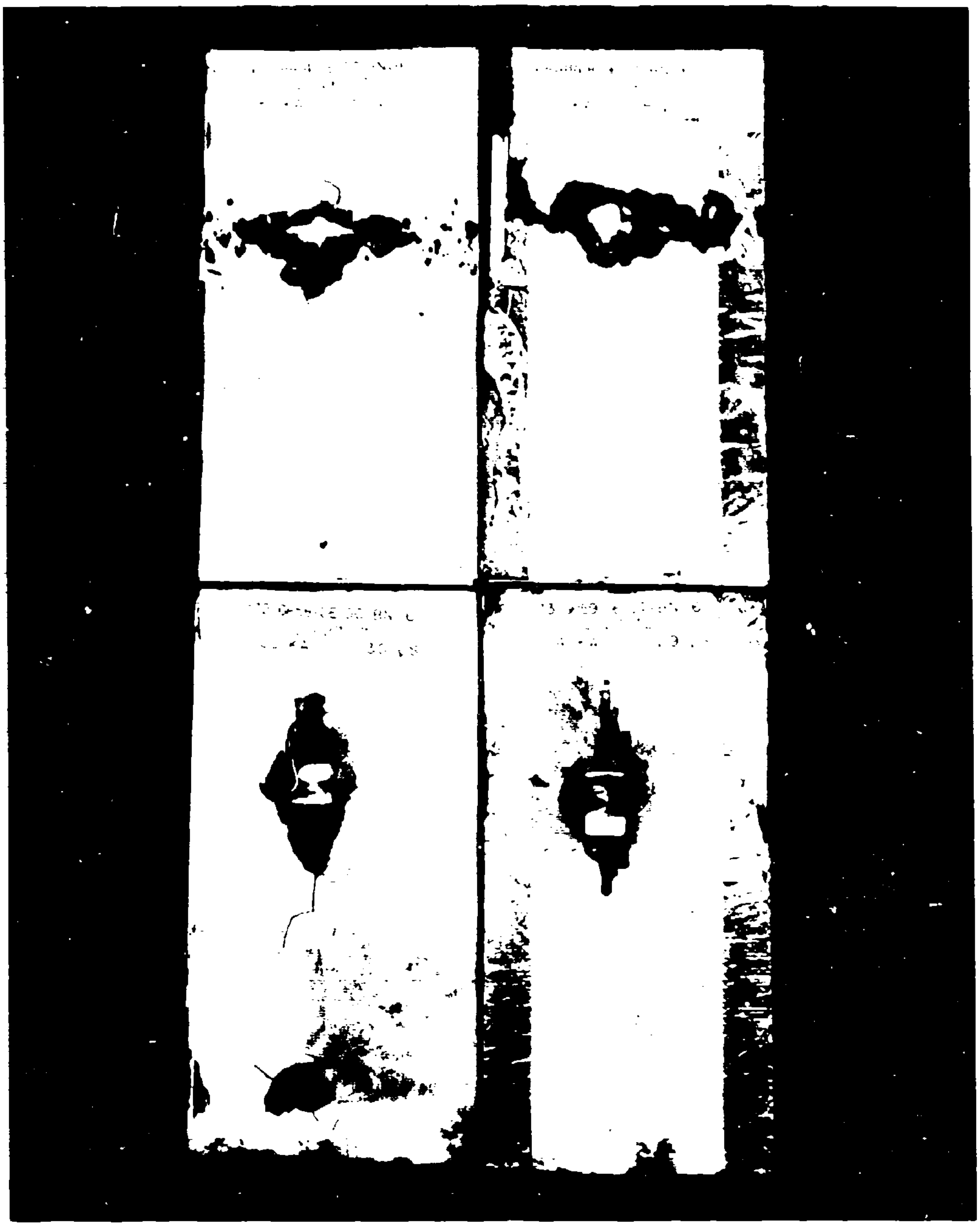
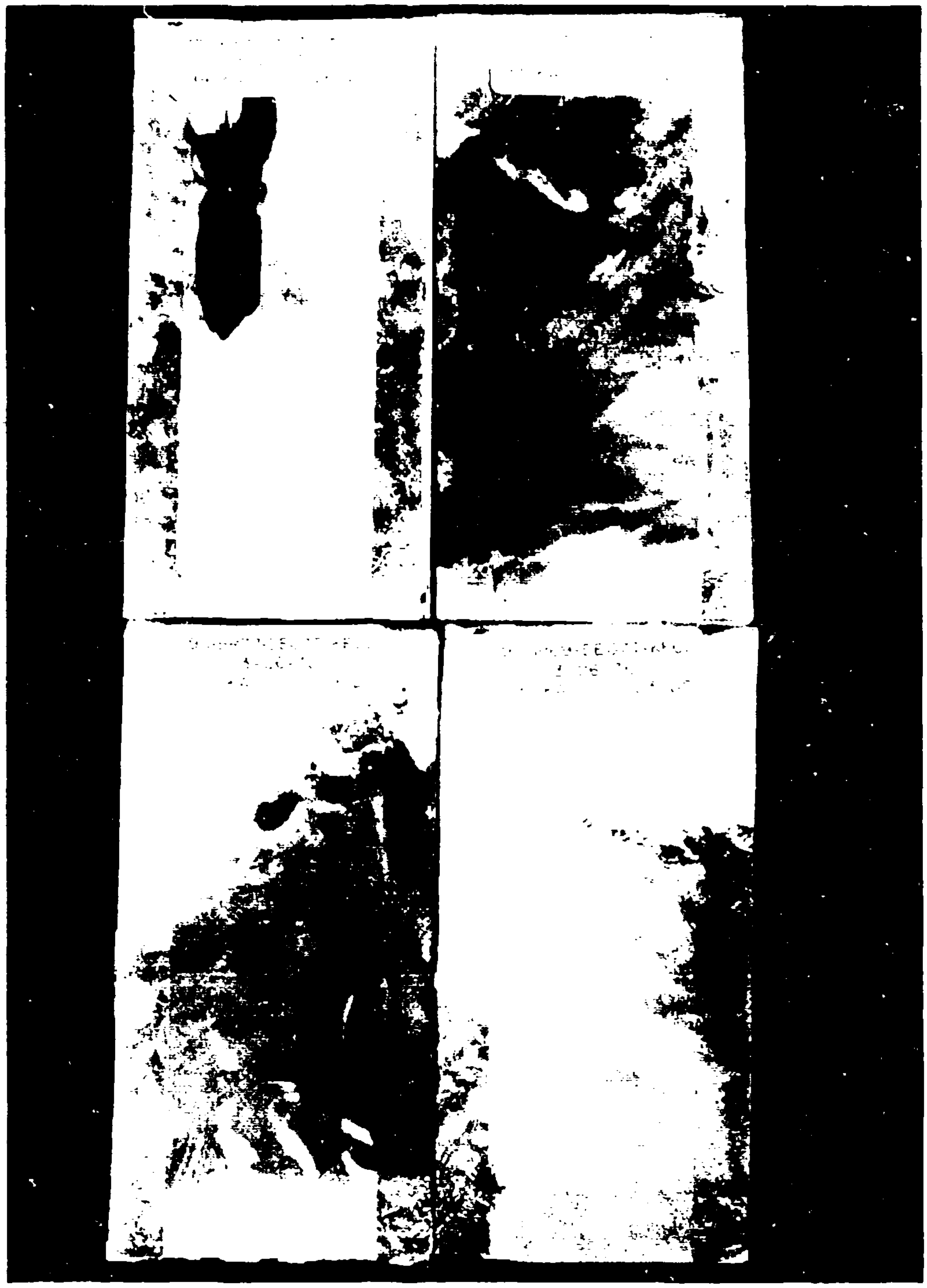


Figure 62 SIMULATED LIGHTNING DISCHARGE DAMAGE TO LAMINATES PAINTED WITH INORGANIC PIGMENTED EPOXY



[illegible] DISCHARGE DAMAGE TO LAMINATE[illegible]
[illegible] EPOXY

The protection offered by these systems is probably due to the dielectric breakdown potential of the epoxy-Kapton combination and the conductivity of the composite substrate. If the breakdown potential through the bulk coating is low, the discharge will penetrate the coating and attach to the reinforcing fibers. If the breakdown potential through the bulk coating is moderate, discharge will first initiate streamers and then flashover the surface and attach to the expendable metal strip. If the breakdown potential through the coating is high, no discharge will be initiated. In this regard, the coating thickness necessary to protect boron reinforcement will be less than that necessary for graphite fiber reinforced plastics; this occurs because of the high dielectric strength provided by the scrim cloth of the boron tape and the insulative boron sheath around the tungsten conductive core of boron filaments. Presumably, the distance between adjacent metal strips is also a critical function for this type of coating; however, the small size of the test panels has prevented a study of this parameter.

It should be pointed out that the discharge to Panel No. 199 was 180 KA (Figure 64). This was the first successful demonstration of surface flashover at this discharge level utilizing a nonconductive coating system.

5.2 FINAL COATING SELECTION AND TESTING

Examination of the results of the screening tests indicates the following:

A. Continuous metal foils at least 1-mil thick can provide effective and efficient lightning protection to high modulus composites.

B. Expendable metal strips can also provide an efficient coating system.

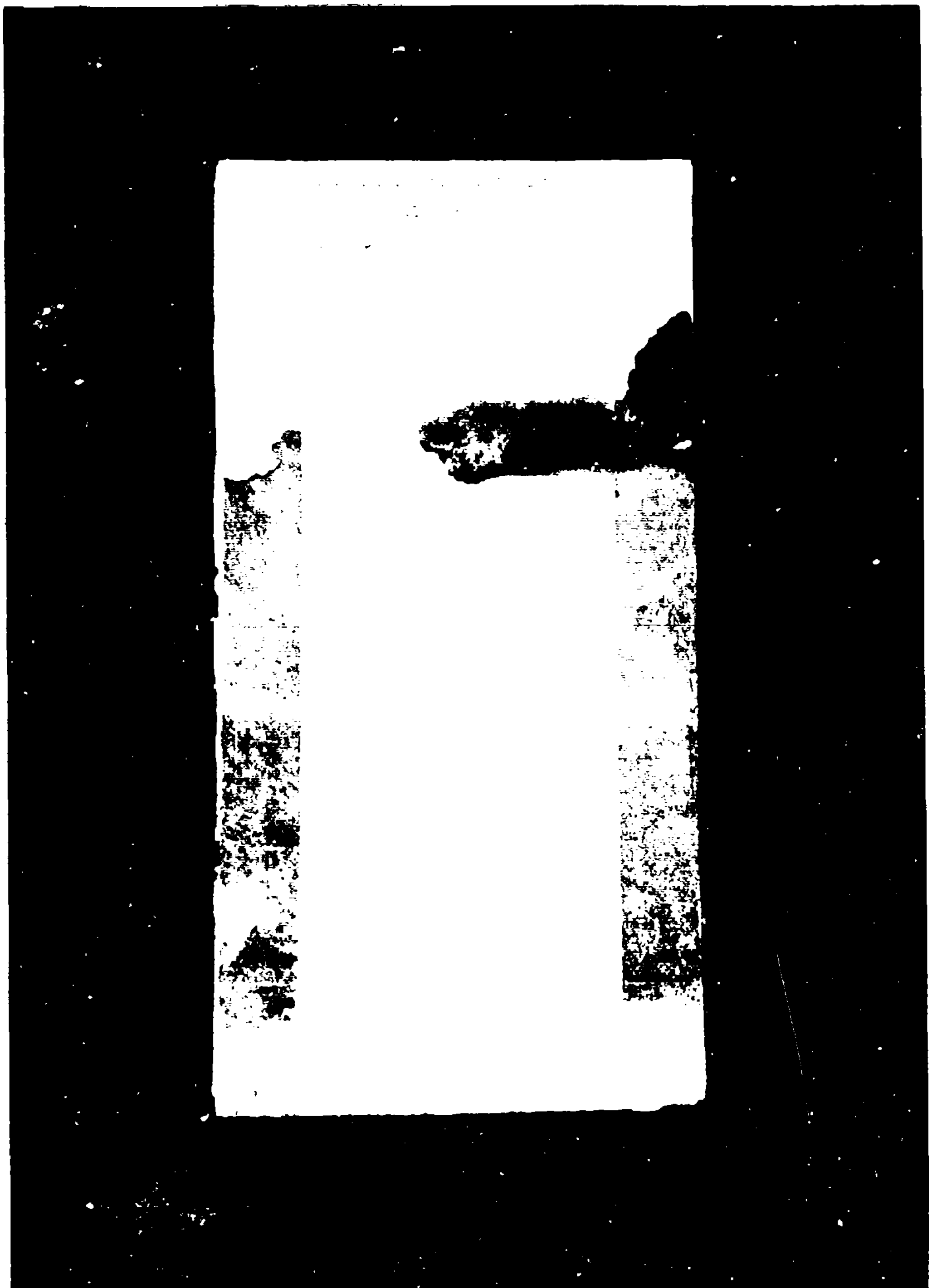
C. Wire fabric coatings provide the most efficient lightning protective system.

D. Knitted fabrics can provide comparable degrees of protection as woven fabrics when comparable amounts of wire per unit area are applied. These systems are highly advantageous from a cost viewpoint.

E. Plasma and flame sprayed aluminum are good coating systems if certain minimum thicknesses are met.

F. Of the metal pigmented paints, only silver provides a conductive coating suitable for lightning protection. Specially treated systems such as silver coated copper are not as efficient.

G. Metal sandwich coatings offered no protection whatsoever unless undercoated with high dielectric strength underlayer.



H. Nonmetallic pigmented paints offer lightning protection when high dielectric strength underlayers are provided. These systems work best when used in conjunction with expendable metal strips.

Consideration of manufacturing difficulties prevents the inclusion of continuous metal foils, strips, plasma or flame sprayed aluminum for the final testing. The desire for a near-term system precludes the use of the nonmetallic systems since they are not well understood and require additional development. Thus, the systems chosen for final development were woven wire fabrics, knitted wire fabrics, and silver pigmented paint with a 1-mil Kapton film undercoating.

A total of 18 samples were tested at the final evaluation task. Each panel was 12 by 12 inches in size and coated with one of the above proposed coating systems. The results of the tests are summarized in Table VI.

5.2.1 Woven Wire Fabric

The woven wire fabric chosen for study was the 200 by 200 mesh aluminum fabric discussed previously. This system has already been shown to offer excellent protection at very high discharge levels. It also provides a significant weight savings over most other coating concepts. Such a weight comparison is shown in Table VII.

Table VII: WEIGHTS OF PROTECTIVE COATING SYSTEMS WITH EQUIVALENT LEVELS OF PROTECTION

Coating	Weight (lbs/100 sq. ft.)
Wire Fabric	3-5
Wire Mesh	5
Aluminum Foil	8.5
Silver Paint	10
Flame Spray Aluminum	8
Dielectric Paints Diverter Strip	8

The fabric itself weighs about 2 lbs/100 sq. ft. When installed by integral bonding methods, the coating weight is about 3 lbs/100 sq. ft. Secondary bonding techniques increase the weight to 5 lbs/100 sq. ft. This is still a considerable weight savings over a 6 mil aluminum foil or an 8 mil silver pigmented paint.

Table VI: SUMMARY OF FINAL TEST RESULTS

PANEL NO.	PROTECTION EFFICIENCY MODERATE I COMPONENT	SEVERE I COMPONENT	HIGH Q COMPONENT
262-GP00-AD08J-0000	Fair		
263-BR12-AD08J-0000	Good		
264-GP01-AR04Z-0000	Good		
265-GP02-SA04C-KF01	Failure		
266-BR13-SA04C-KF01	Failure		
267-BR14-AR04Z-0000	Good		
268-BR15-AR04Z-0000			Good (20 coul)
269-GP03-AR04Z-0000			Fair
270-GP04-SA04C-KF01			Failure
271-GP05-AD08J-0000			Fair
272-BR15-AD08J-0000			Fair (hot spot)
273-BR16-SA04C-KF01	Good (60 KA)		
274-BR17-SA04C-KF01	Failure		
275-GP06-SA04C-KF01		Failure	
276-BR18-AD08J-0000		Good	
277-BR19-AR04Z-0000		Good	
278-GP07-AR04Z-0000		Good	
279-GP08-AD08J-0000		Fair	

NOTE: Code for panels - see Table IV.

Moderate I Comp - approximate 100 KA
Severe I Comp - approximate 200 KA
High Q Comp - high coulomb component

Environmentally, the coating appears extremely stable. The aluminum metal alloy 5056 is one of the better corrosion resistant materials available. It is also one of the most conductive aluminum alloys. The matrices chosen for this study are very stable in normal aircraft environments. Some loss of composite properties are to be expected after prolonged environmental exposure, but these are minimal.

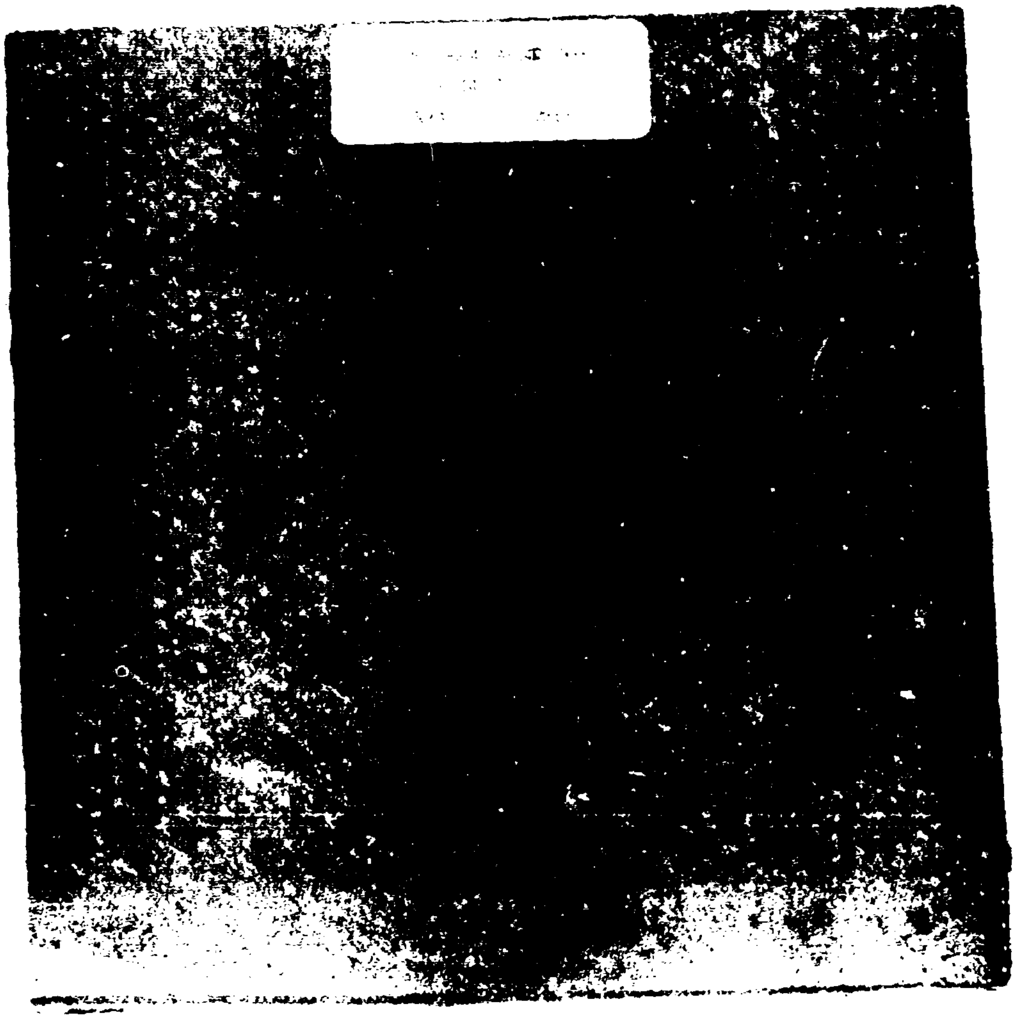
The results of artificial lightning discharges directed toward boron filament and graphite fiber composites coated with this coating system are shown in Figures 65-70. Figure 65 shows the damage sustained by a sixteen ply, 12-inch square boron fiber reinforced composite at a 130 KA discharge; as can be clearly seen, only the fabric is damaged. A slightly lower discharge to a graphite fiber composite is shown in Figure 66. The coating was vaporized from the surface in a half-square inch area at the arc contact point, but otherwise the system behaves much the same as for the boron composite. At this discharge level, the system provides extremely good protection of boron and graphite reinforced plastics.

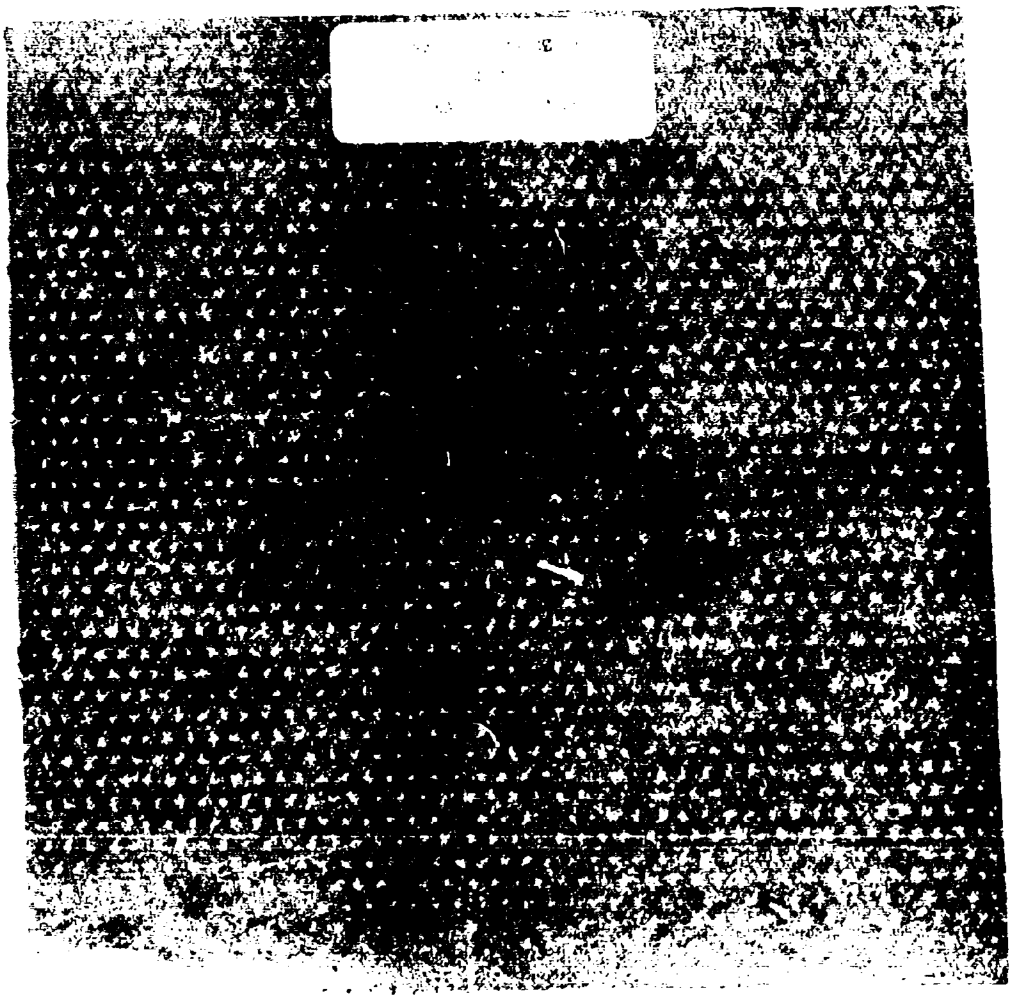
At 200 KA discharge, the damage to a boron panel is restricted again to the coating as shown in Figure 67. The coating was not punctured although resin scorching occurred in the contact area. The area of extreme damage to the coating is larger in this case, but a minor amount of aluminum still exists in the contact zone. This illustrates the ability of wire fabrics to conduct currents with little damage to the wire. No other coating concept performs as well at these discharge levels.

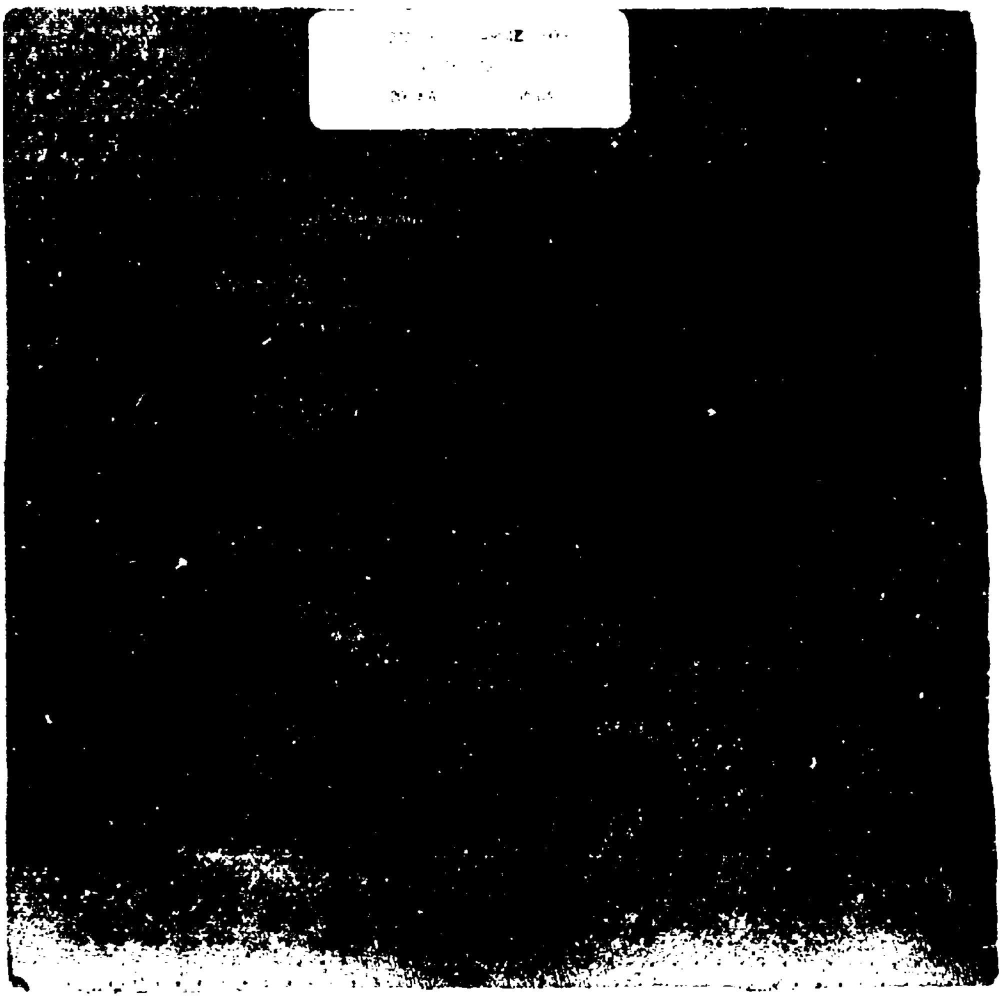
The comparable discharge to a graphite fiber reinforced composite is shown in Figure 68. Here a 1-inch square of metal fabric was destroyed. The resin under this 1 inch was scorched and some delamination of the outer fiber ply occurred. This is a minor damage since delamination in graphite composites usually occurs explosively and results in the complete destruction of one or more laminate plies. This coating has displayed excellent surface flashover characteristics from the results of the above high amperage tests.

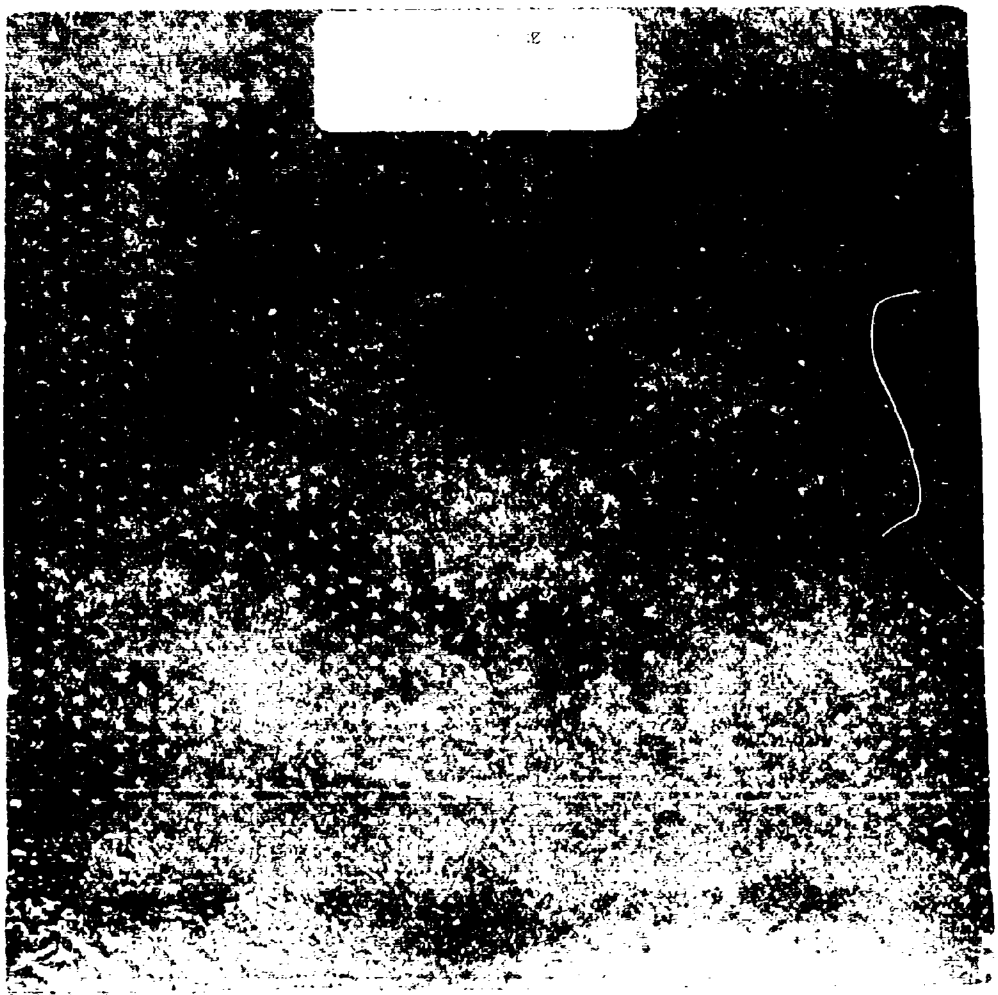
Figure 69 shows the result of a 256-coulomb transfer test to a fourteen ply, 12-inch square graphite composite. The arc burned a 1-3/4 by 1-3/4 diamond-shaped mark on the test panel. Smaller areas of the first five plies of this fourteen ply laminate were destroyed. The blackened surface of the panel is d· · to char deposits from the resin. Other than at the arc zone, no damage to the composite was observed.

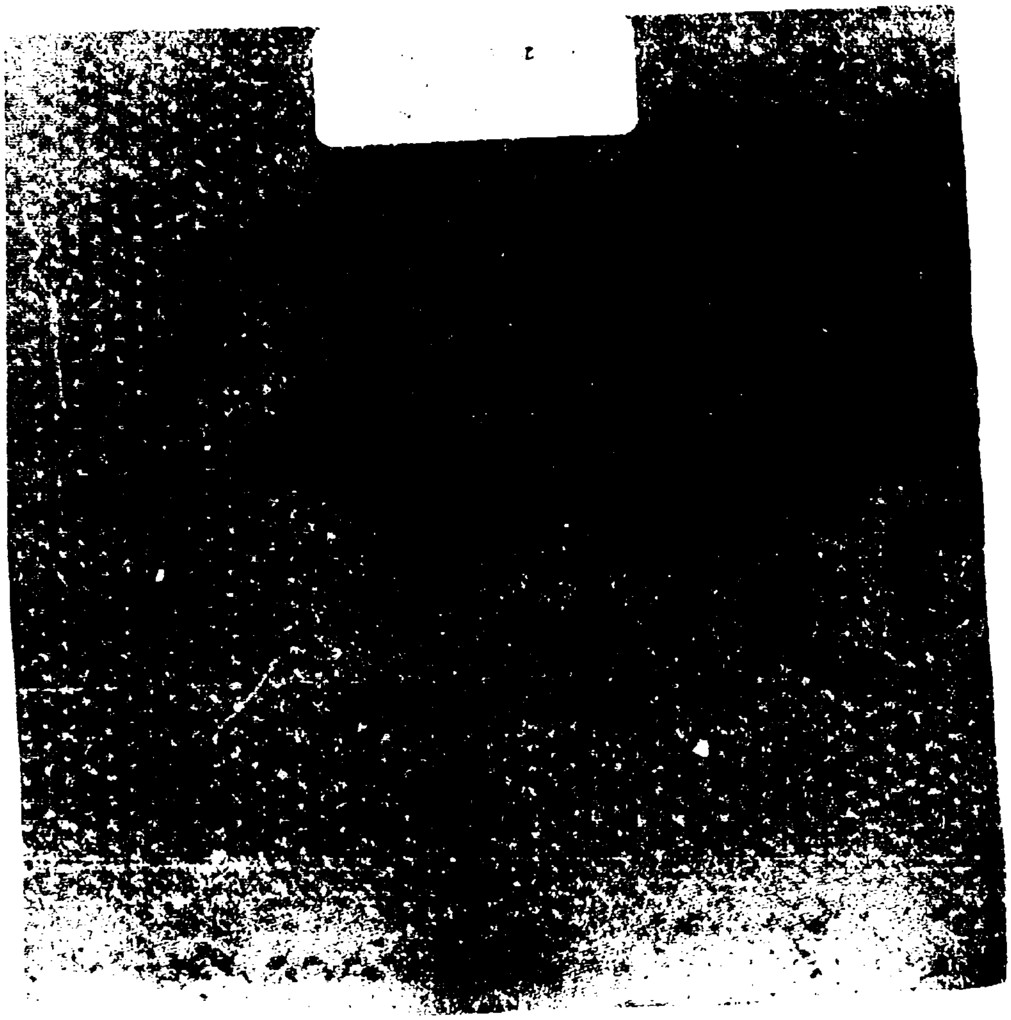
A similar, but smaller coulomb transfer test was applied to a boron composite. The arc terminated prematurely and a total of 20 coulombs were transferred to the coated panel. As illustrated in Figure 70, the coating displays the markings characteristic of surface flashover. Some destruction of the coating at a point 3 inches from the contact zone was observed. A 1-inch diameter spot at the contact zone illustrates thermal damage to the resin. Undoubtedly additional damage would have occurred for a longer dwell time.

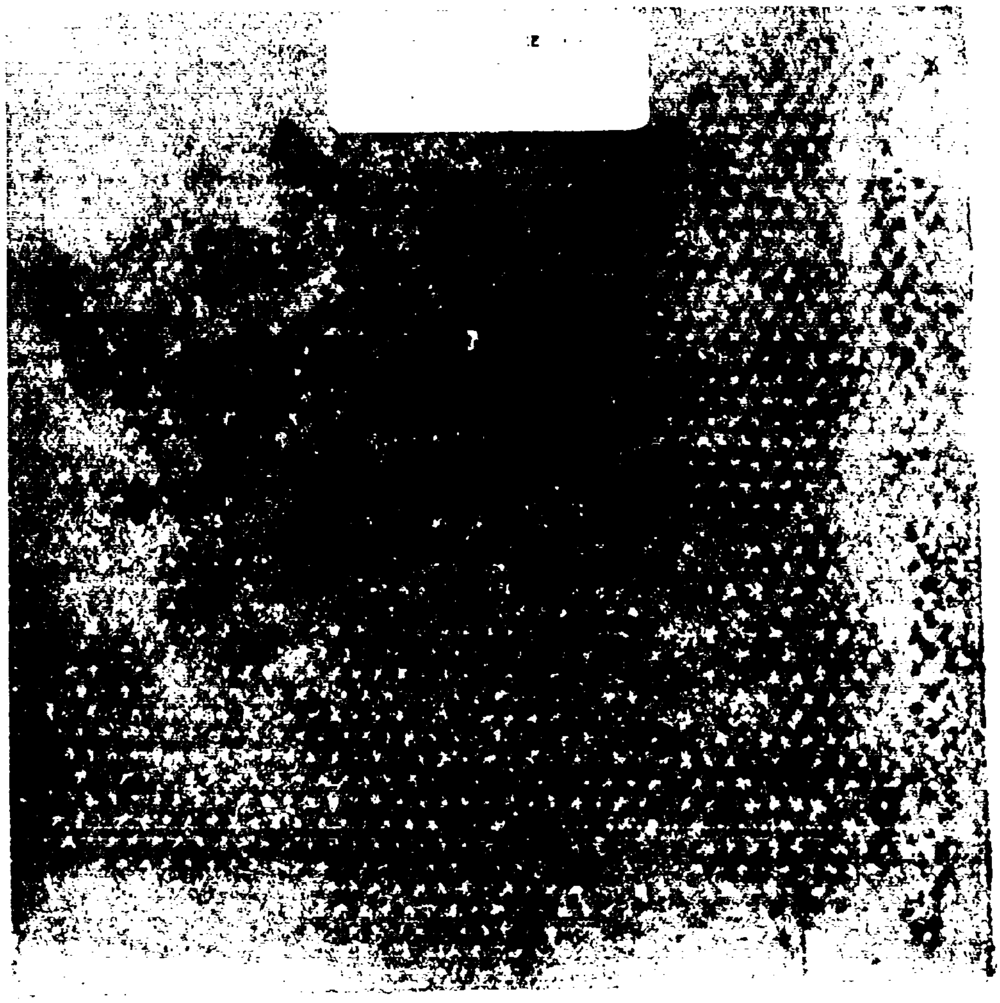












Samples were removed from the test panels and submitted to physical tests to determine their physical properties. Test coupons were taken from the contact zone and along the contact zone-electrical ground axis; control specimens were cut from an area near the edge of the panels and away from the arc contact zone and the electrical ground.

Structural damage to the boron composites panels was not detected by these flexural tests. The test coupons from the 130 KA test panel gave an average flexural modulus of 21.6 $\pm$ 0.3 MSI (five specimen average; calculations include the coating as part of specimen depth). The coupon cut from directly under the contact zone had a modulus of 21.0 MSI. No change in the strength was noted either. A very minor amount of damage may have been incurred by the 200 KA discharge. This panel had a flexural modulus of 16.4 MSI. Nevertheless, the flexural strength of this coupon was 90.0 ksi compared with an average of 92.0 for the controls. Since both the flexural strength and flexural modulus are somewhat less than the control average, a small amount of damage may have occurred. It should be pointed out that the damage is minor in terms of flexural properties and was only detected at the arc contact spot. Coupons taken from along the arc contact-electrical ground axis were indistinguishable from the controls. Similarly, only the coupon taken from directly under the contact zone was observed to be damaged on the 20-coulomb test panel.

Thus, it is apparent that this wire fabric coating system has provided excellent lightning protection to the boron reinforced composite panels. Mechanical damage was undetectable after a 130 KA discharge and barely detectable after a 200 KA or a 20-coulomb discharge. The detectable damage amounted to a 12 percent reduction in flexural modulus at the exact arc contact. No damage could be detected outside a 3-inch radius surrounding this point.

The reduction in mechanical properties was even less for the graphite reinforced composite panels. Coupons taken from the 220 KA test panel possessed an average flexural modulus of 15.1 $\pm$ 0.4 MSI. Coupons taken from 1 inch of either side of the arc contact zone possessed flexural moduli of 15.2 and 15.3 MSI. Thus, it is certain that any reduction in mechanical properties is not observed at distances greater than 2 inches from the arc contact. At the contact, some damage has occurred as the outer ply of the laminate has been scorched and the resin burned off. Tests of the 256 coulomb graphite fiber composite panel displayed a similar behavior. An average control modulus of 15.5 $\pm$ .2 MSI was found. Coupons cut with their centers 2 inches from arc contact possessed moduli of 11.6 MSI (toward electrical ground) and 13.3 MSI (away from electrical ground), respectively. Five inches from this zone, close to electrical ground, the flexural modulus was again 15.5 MSI. Thus, it can be concluded that little damage to the composite panels has occurred even though the damage due to high coulomb transfer tests is more than that inflicted by high amperage discharge tests.

The better protection of the graphite composite panel points out the great efficiency of this coating system as the reverse order of damage occurs when uncoated boron and graphite panels are tested.

5.2.2 Knitted Wire Mesh

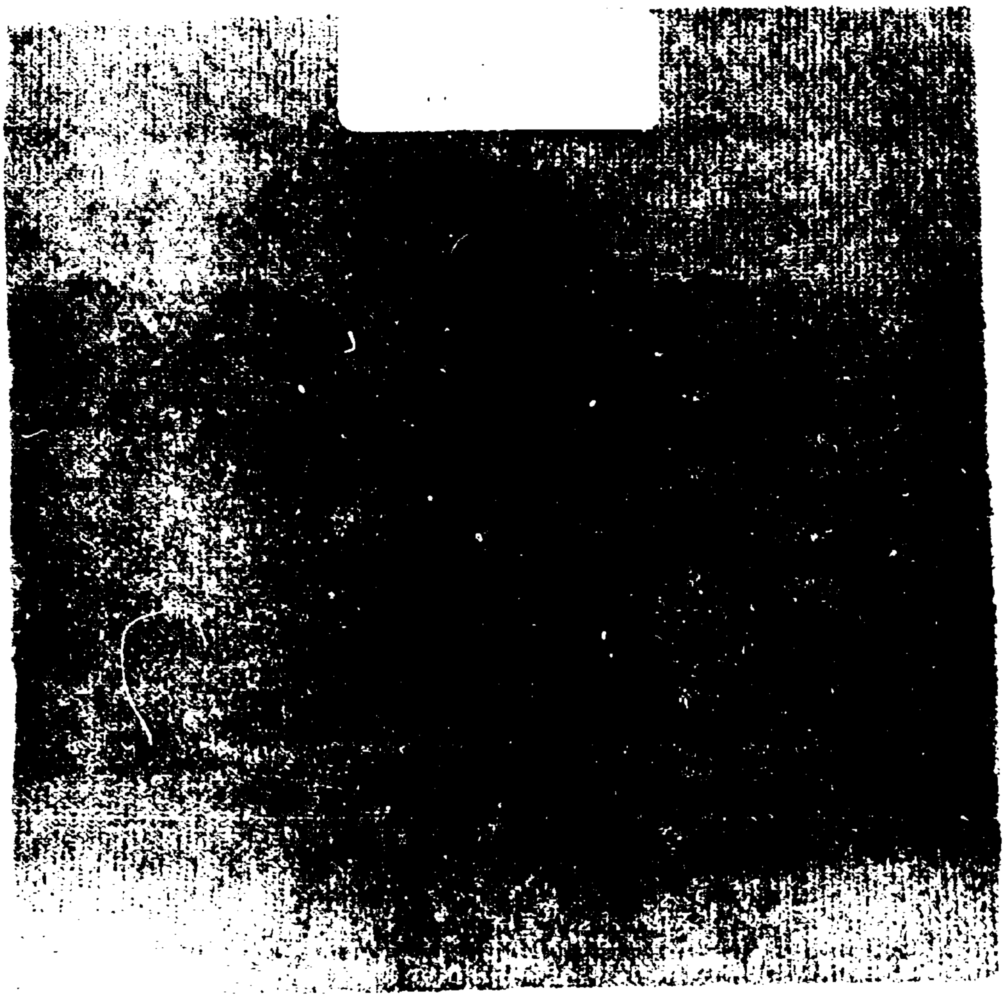
The knitted wire mesh chosen for this study was a two-stranded, 4-mil diameter aluminum wire with 13 by 24 mesh. A photograph of this mesh is shown in Figure 1b. The double stranded wire allows an increase in the amount of aluminum on the surface of the composite but does not increase coating thickness. The double stranded wire has a metal density per unit area comparable to the successful larger diameter wire coatings. Parameters of this coating system are illustrated in Table 1.

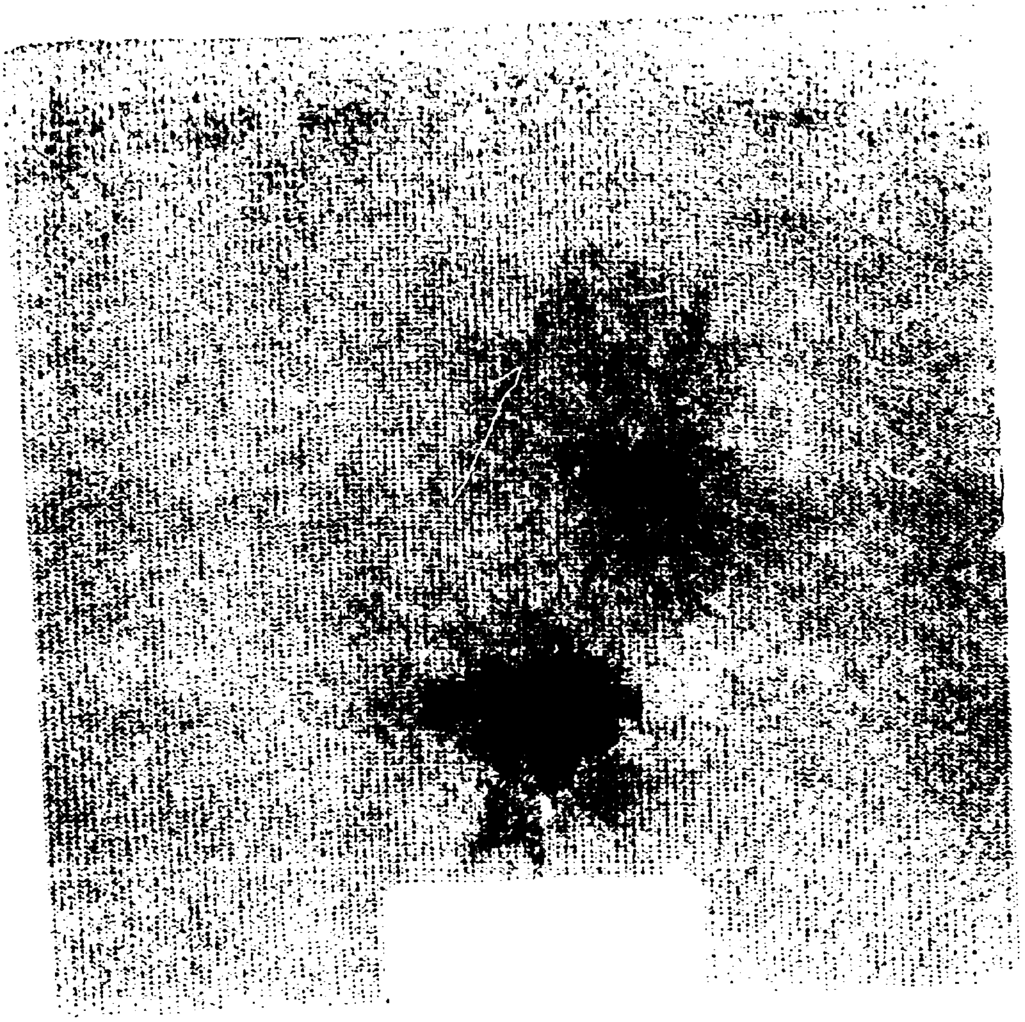
One-hundred KA discharges to this fabric have found it to provide excellent protection to boron but lesser protection to graphite. The boron composite shows no damage except that much of the mesh has been burned away in the area surrounding the arc contact as shown in Figure 71. The graphite panel was damaged slightly as a 2 by 3-inch area of the mesh was evaporated and destroyed. This is shown in Figure 72. Some scorching of the resin below this area occurred. Nevertheless, the damage to the composite is minimal as the coating conducted most of the lightning current.

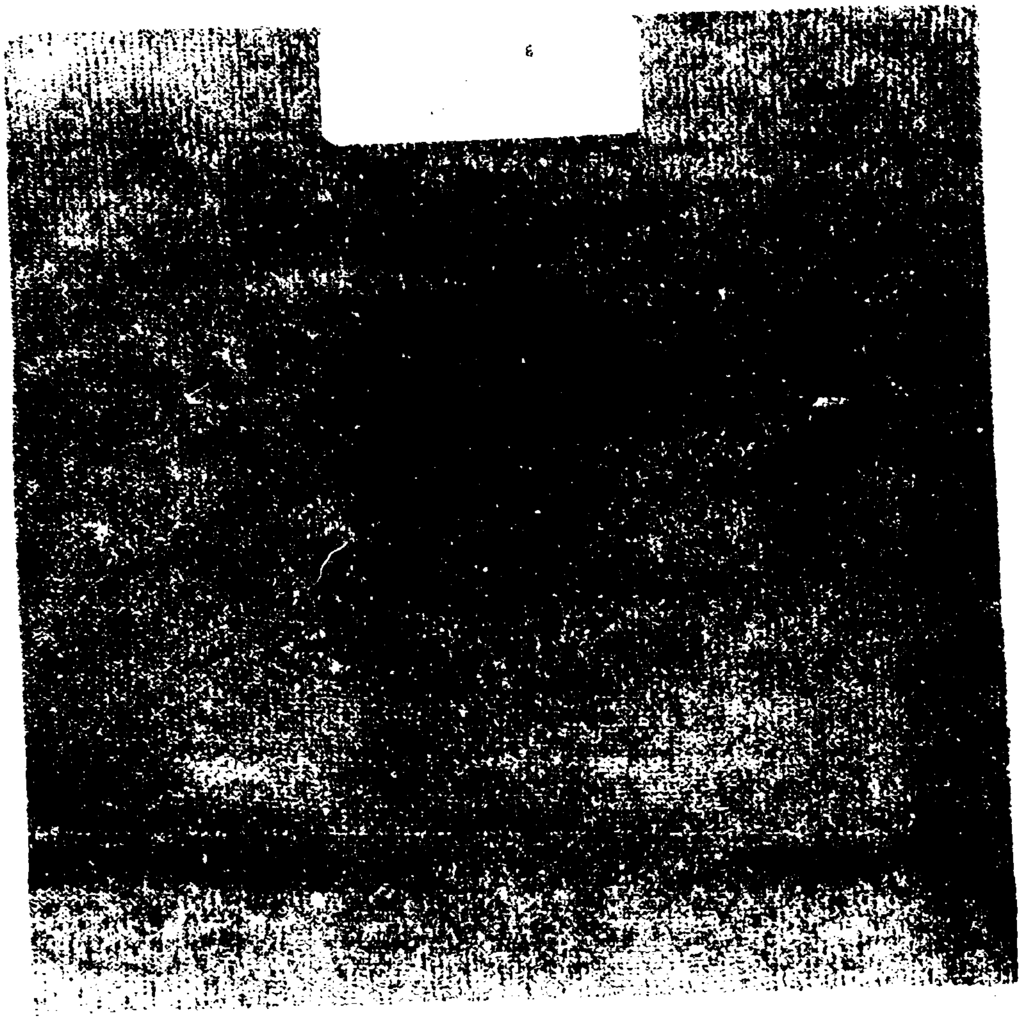
At the 210 KA discharge level, the graphite panel was more severely damaged (Figure 73). A 2 by 5-inch piece of the outer ply of the panel was delaminated and some resin scorching of the second ply was observed. A comparable discharge to the boron composite resulted in damage to the coating only (Figure 74). Thus, the knitted wire mesh provides excellent protection to boron filament reinforced plastics and good protection to graphite fiber reinforced plastics. Further improvements of this system might attempt to increase the mesh density, thus providing a more uniform metal density.

The results of high coulomb transfer tests to panels coated with knitted wire mesh are shown in Figure 75 and 76. A 100-coulomb transfer test to a boron composite resulted in the burning of some of the coating and a square inch of the composite. The current flow to electrical ground is easily discernable as the resin in this area was severely scorched. A burn mark at the ground contact was also observed. A 200-coulomb transfer test to a graphite fiber reinforced composite yielded the damage of a 1 by 2-inch section of the outer ply of graphite.

It is apparent from these tests that the coating does not provide complete protection against high coulomb transfer. The coating dissipates some of the charge but significant burn damage to the composites occurs. For comparison purposes, the degree of damage to aluminum sheet is illustrated in Figure 77. This 263-coulomb transfer test burned a 1 inch hole completely through a sheet of 0.040" aluminum. That the arc temperatures can destroy boron or graphite is illustrated in Figure 78. This electron scanning view of the boron at the arc contact shows re-solidified boron, aluminum and tungsten at the high temperature burn







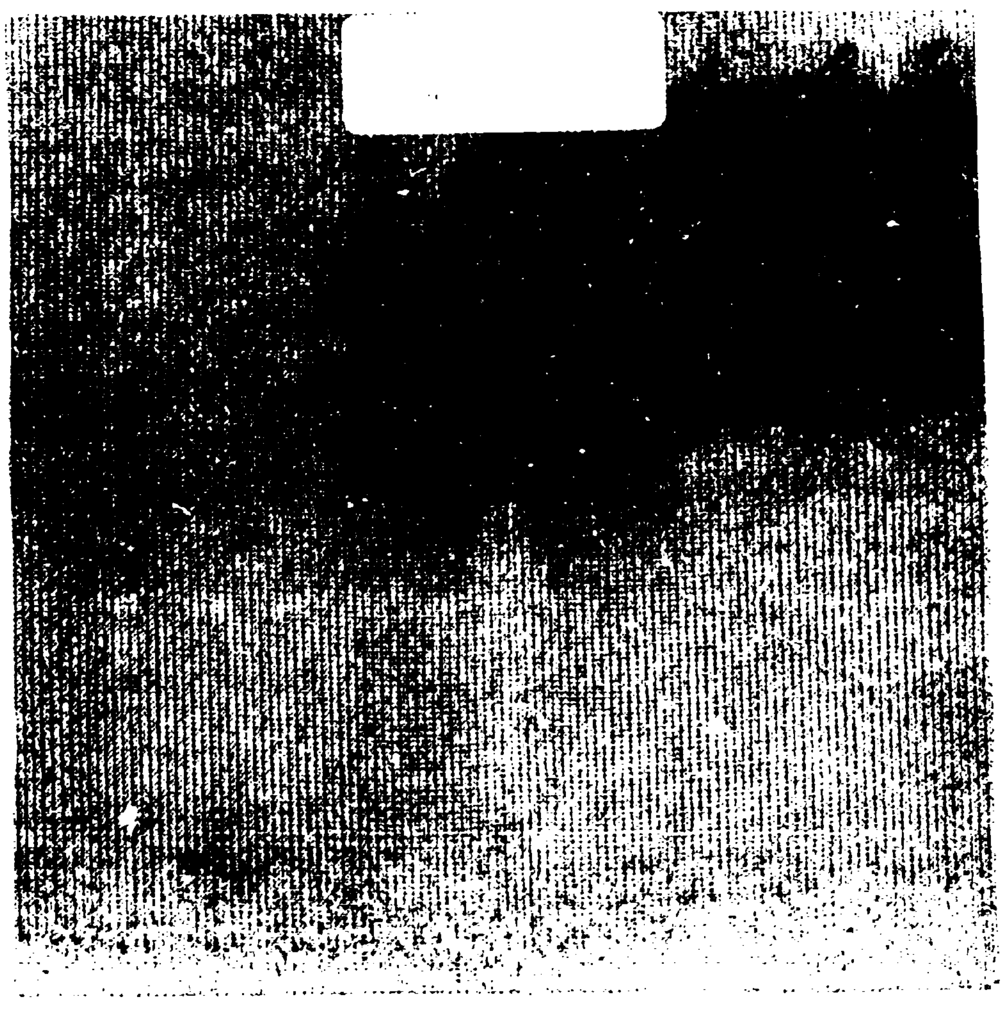


Figure 77. 262 COULOMB TRANSFER DAMAGE TO AN 0.040 SHEET OF ALUMINUM.

zone. Figure 78 depicts an area near the edge of the burn zone. The material in the lower right hand corner was melted and has resolidified. The material to the upper left side of the picture has not been thermally damaged, although the resin has been removed. Obviously the temperature gradient at the burn zone boundaries was extreme. Closeup views of the burn area show two different phenomena. This is probably due to differences in chemical composition, or differences in thermal history. Figure 79 shows several nodular type crystal growths. These are particularly prominent about the edges of the holes in the sample and are probably representative of material from under the surface of this damaged area. The hot gases within the composite expanded through the molten composite. Sudden resolidification deposits the material about the exit holes and does not allow the material to flow and close the openings. Another view (Figure 80) illustrates a decidely different behaviour. This area is covered with a needle-like crystal growth. This is probably due to different chemical composition or may be due to slow cooling of the melt which permitted the crystals to form. In light of this type of burn damage and in view of the thickness of aluminum sheet required to prevent burn through, it is unlikely that a coating can completely prevent this type of damage to advanced composites. However, the mechanical strength test has shown the damage is limited to a very small zone about the arc contact point.

Residual flexural strengths were determined for the lightning tested panels. Test coupons were prepared as described for the woven wire fabric coated panels. The coupons from the test area possessed the same modulus as the controls and were not damaged mechanically at a 100 KA discharge level. Test coupons from the 220 KA test panel possessed an average flexural modulus of 16.4 $\pm$ 0.4 MSI. Coupons from the test area had residual moduli of 14.9, 15.3 and 16.7 MSI. The scatter in data is due in part to the coating. The coating adds no strength to the composite structure, but does reduce the apparent mechanical properties, such as flexural strength and modulus. For these tests the coating was included in mechanical test coupon thickness determination.

A 100-coulomb transfer test burned a small hole in the outer ply of the boron composite and destroyed some of the filaments going to electrical ground. This damage was reflected in the lower flexural modulus of the composite. A control of 15.1 $\pm$ 0.1 MSI was determined. The test area and contact ground axis had values of 14.0, 14.4 and 14.7 MSI. The higher values were more removed from the burn area. The low value of 14.0 MSI was determined for a coupon centered from the edge of the burn spot.

The graphite panels were also subjected to residual flexural modulus tests. The 210 KA test panel yielded specimens with residual moduli which were 90 percent of control. Coupons taken from the contact-electrical ground axis were not damaged as their modulus in flexure was the same as the control.

Figure 78   SEM VIEW OF DAMAGED BORON FILAMENTS

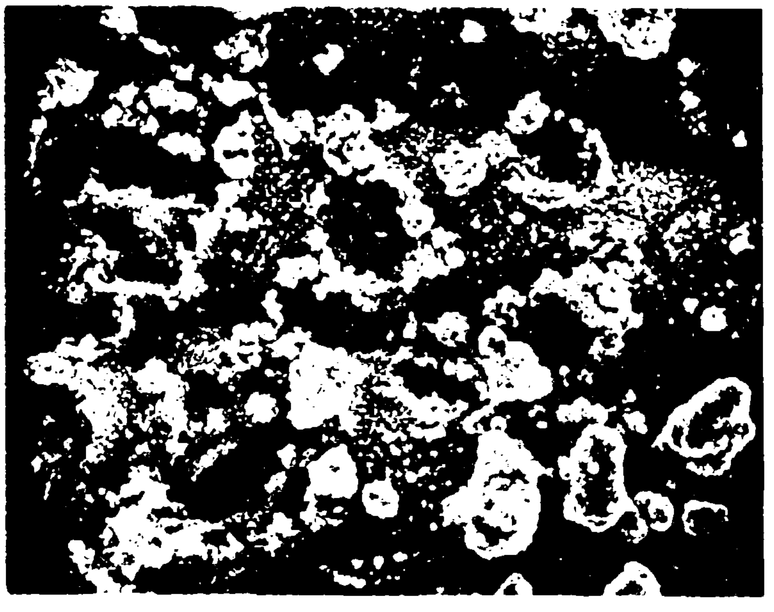
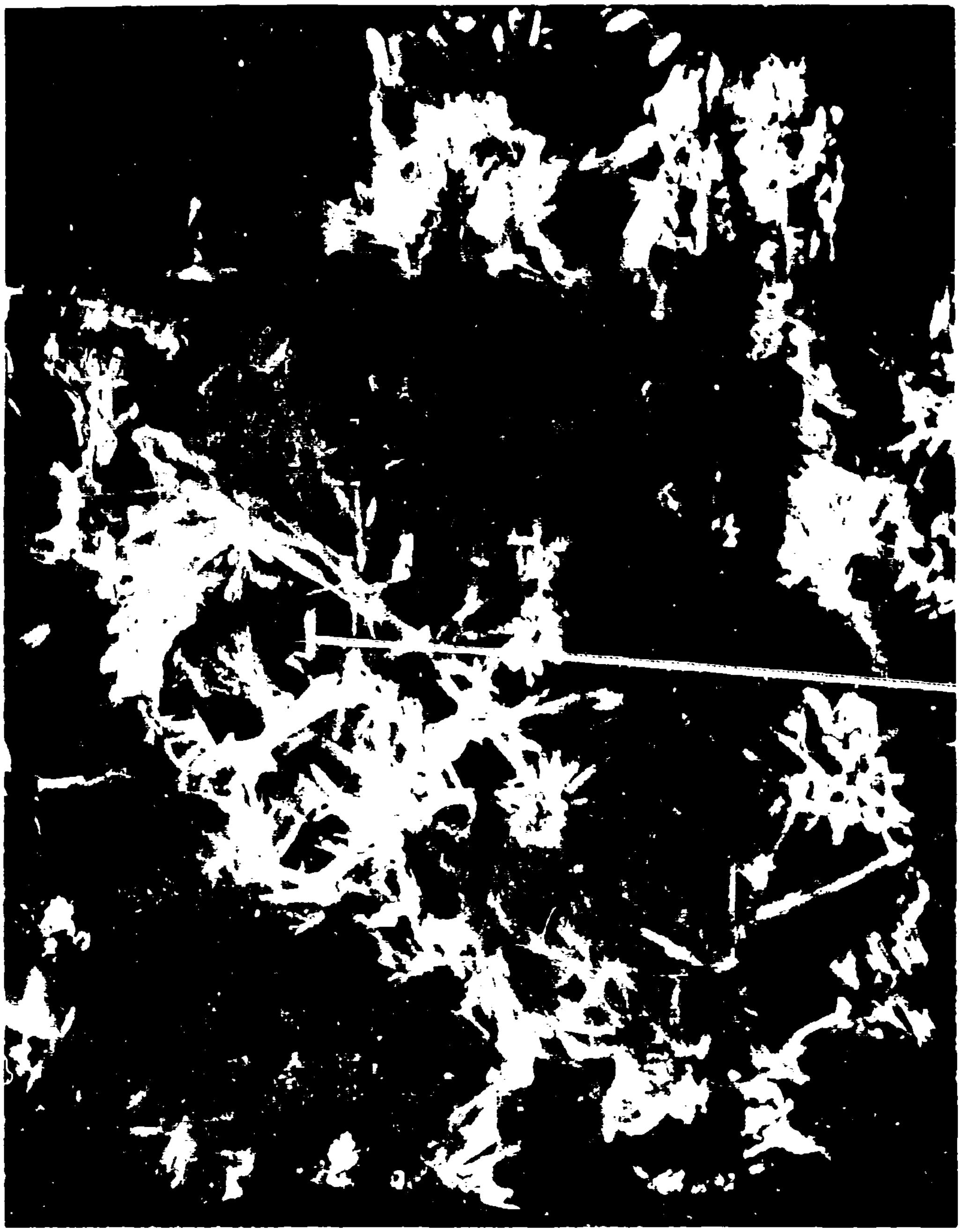


Figure 79   SEM VIEW OF DAMAGED BORON FILAMENTS



The graphite panel used for the 200-coulomb test was weakened at the contact zone. The specimens cut from the contact-electrical ground axis had moduli of 80-90 percent of the controls.

In summary, the knitted wire mesh provides excellent protection to boron reinforced plastics and good protection to the graphite reinforced composite. Reductions in flexural modulus at the contact zone were found at high current discharge levels, but these were limited to areas less than 3 inches in diameter. High coulomb transfer tests cause more extensive damage than do the high amperage discharges.

5.2.3 Silver Pigmented Conductive Coating

Of the metal pigmented paints, only those pigmented with silver provide the conductivity necessary for lightning protection. Nevertheless, these paints are prohibitively heavy due to the density and amount of silver required for even moderate degrees of lightning protection. Screening studies have shown 4 mils of silver paint with expendable metal strips attached to the panel edges can provide a moderate level of protection, however, 6 mils of coating are required when no modifications to the basic paint are made. An 8-mil coating is recommended for high current level discharge protection. Consequently an attempt was made to reduce the weight of that coating. The method chosen was to utilize a Kapton film dielectric underlayer in conjunction with the coating.

The 1-mil Kapton film underlayers were integrally bonded to the laminates during cure. The Kapton was primed with 0.2-mil of BMS 10-11, Type I epoxy primer and then painted with a silver pigmented acrylic conductive coating of 4.0 $\pm$ 0.2 mils thick. After application, the coating was baked for 2 hours at 240°F. Care was taken to assure that continuous wet films were maintained during coating application. This is to assure good conductivity.

The conductive coating was an acrylic based resin and consequently possesses only limited solvent resistance. Thinners and solvents such as hydraulic fluids will remove the coating. In all other respects the coating is very stable to the environment. Conductivity does not change after 100 hours in salt spray, 350°F aging or the weatherometer. The environmental stability of coatings of this type is due to the stability of silver. This is the chief factor in determining the electrical behavior of the coating.

The coating did not protect the boron composite from an 80 KA discharge. A 1 by 5-inch piece of the outer ply was destroyed and some resin scorching in the remaining plies was observed (Figure 81). The lesser degree of discoloration of the surface indicates the fibers carried a large amount of the discharge. In addition, the coating was burned at the ground attachment. This is due to arcing from the fibers to the ground attachment. At the 120 KA discharge level, the panel was punctured and a sizable area of boron was delaminated. Blistering at the ground attachment was also observed (Figure 82).

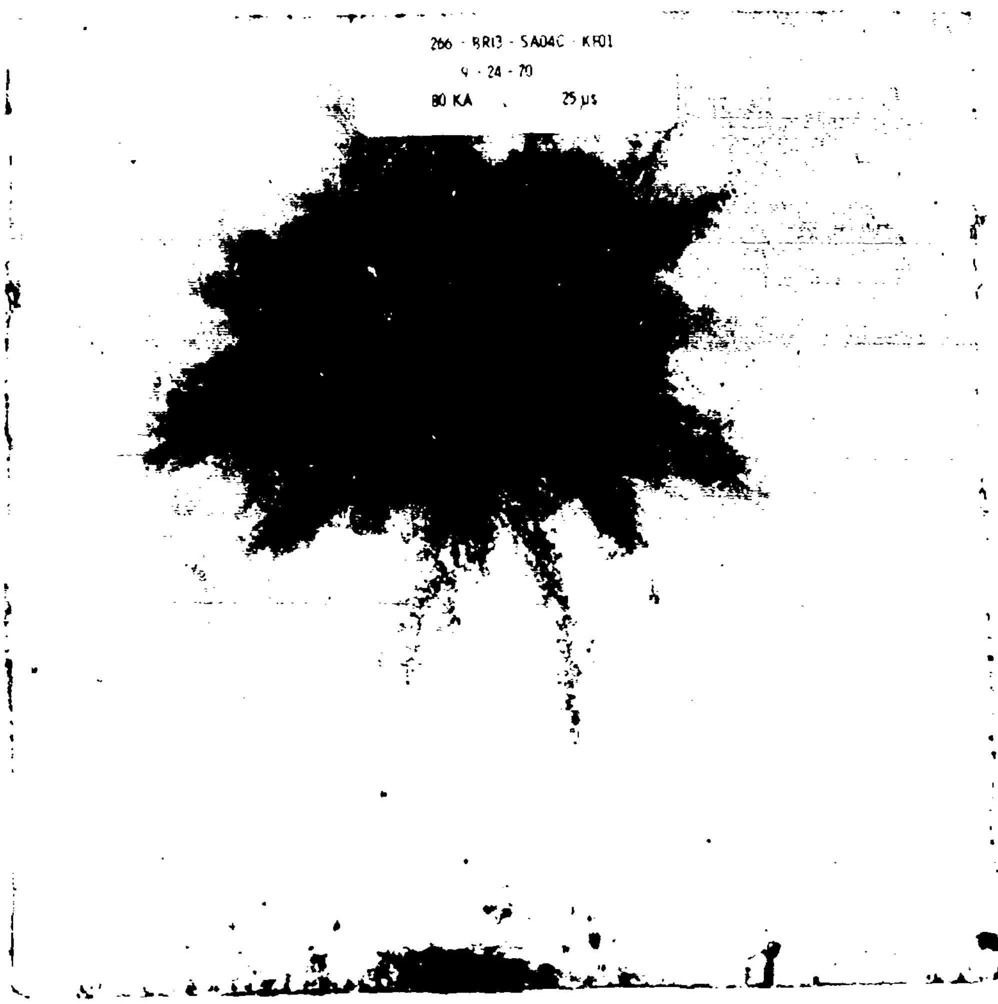


Figure 81 80 KA DISCHARGE DAMAGE TO SILVER COATED BORON EPOXY LAMINATE

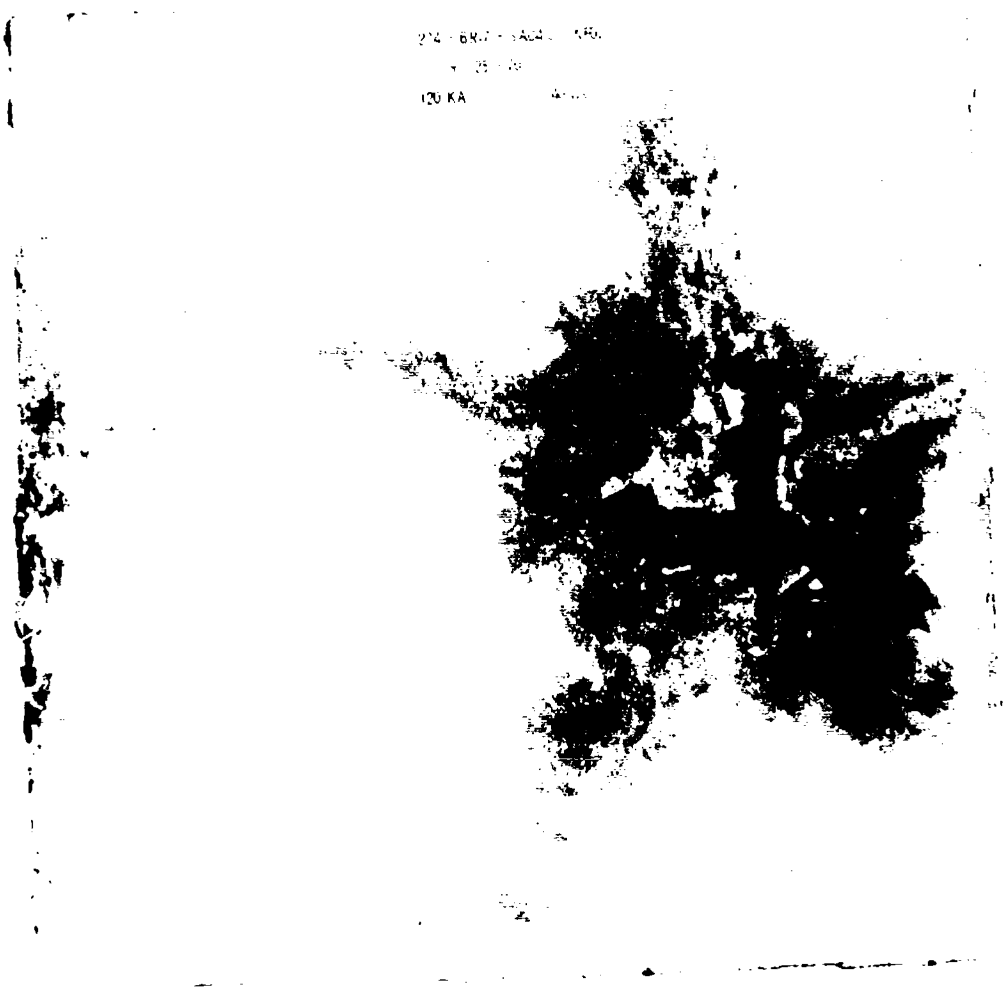


Figure 82 120 KA DISCHARGE DAMAGE TO SILVER COATED BORON EPOXY LAMINATE

A third boron substrate was tested at a lower current level instead of the high coulomb test as originally planned. The reasons for this change are:

A. The failure of this coating to a high coulomb test was expected.

B. A possible application of this coating system to a boron substrate at a lower current level.

A 60 KA discharge was therefore initiated to the last boron sample. At 60 KA, an arc to a boron reinforced composite neither damaged nor punctured the coating and a colored flashover pattern was left on the panel surface as shown in Figure 83.

While this coating was not successful in protecting boron fiber reinforced composites from lightning damage, it must be concluded that it provides better protection to graphite than to boron. A 100 KA discharge to the graphite composite delaminated a 1 by 5-inch piece of the outer ply and caused resin scorching of the second ply as shown in Figure 84. Some conduction by the fibers is illustrated by the burn marks at the electrical ground. A 180 KA discharge punctured the graphite composite and caused severe delamination at the ground attachment (Figure 85). Although structurally significant, this damage level is less than that sustained by a boron composite at comparable discharge levels. A 202-coulomb test burned a 1-inch hole in a conductive silver coated graphite composite. A 2 by 4-inch piece of the outer ply was explosively delaminated from the panel and a small amount of burning at the ground attachment can be seen as shown in Figure 86.

Mechanical tests were performed on test coupons removed from these lightning tested panels. The boron panel subjected to a 60 KA discharge displayed no evidence of loss in flexural strength or modulus and was effectively protected by this coating. The test panels were damaged by 80 and 120 KA discharges. Coupons taken from the test area possessed 25 percent or less of control modulus and strength. Test coupons taken from visibly undamaged areas near electrical ground possessed only 50 percent of original strength. Thus, the damage to the boron panel is partly hidden by the remaining intact coating.

The graphite composite panel was much stronger and stiffer. Coupons from the test panel subjected to the 180 KA discharge were removed from along the contact area-electrical ground axis. All of these possessed at least 80 percent of their original mechanical properties. Additionally, the 202 coulomb test panel was found to possess 90 percent of original flexural strength and modulus for samples taken with 4 inches from the damage zone. Thus, it is concluded that graphite composites are less easily damaged by directly injected electrical currents. The damage to graphite fiber reinforced composites is primarily limited to the immediate vicinity of the arc contact. In boron reinforced composites, damage to the fibers may travel the full length of the fibers themselves.

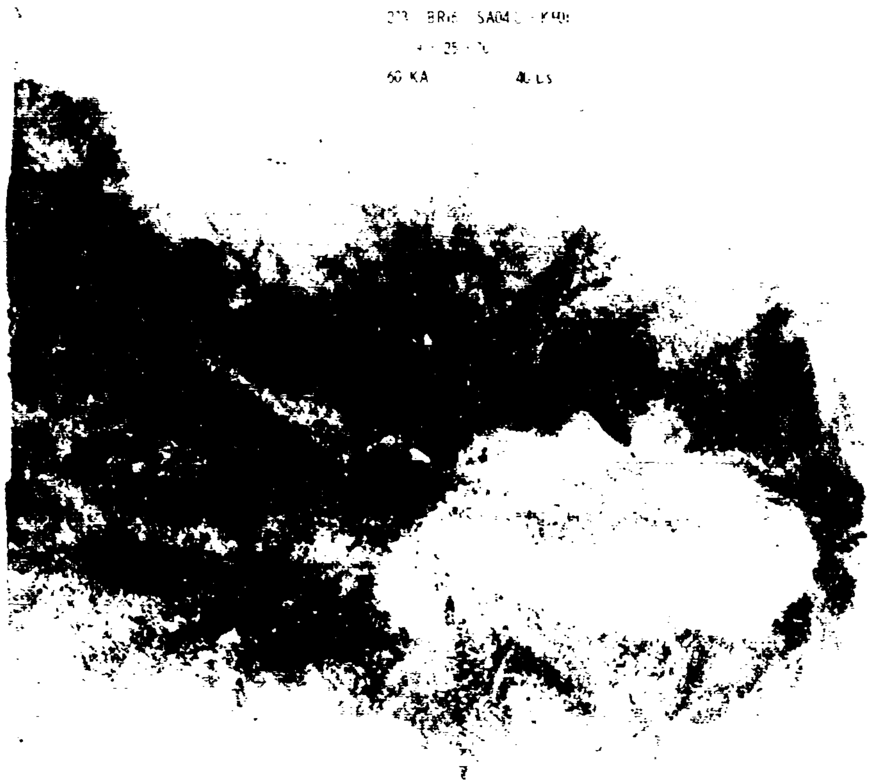


Figure 83 60 KA DISCHARGE DAMAGE TO SILVER COATED BORON EPOXY LAMINATE

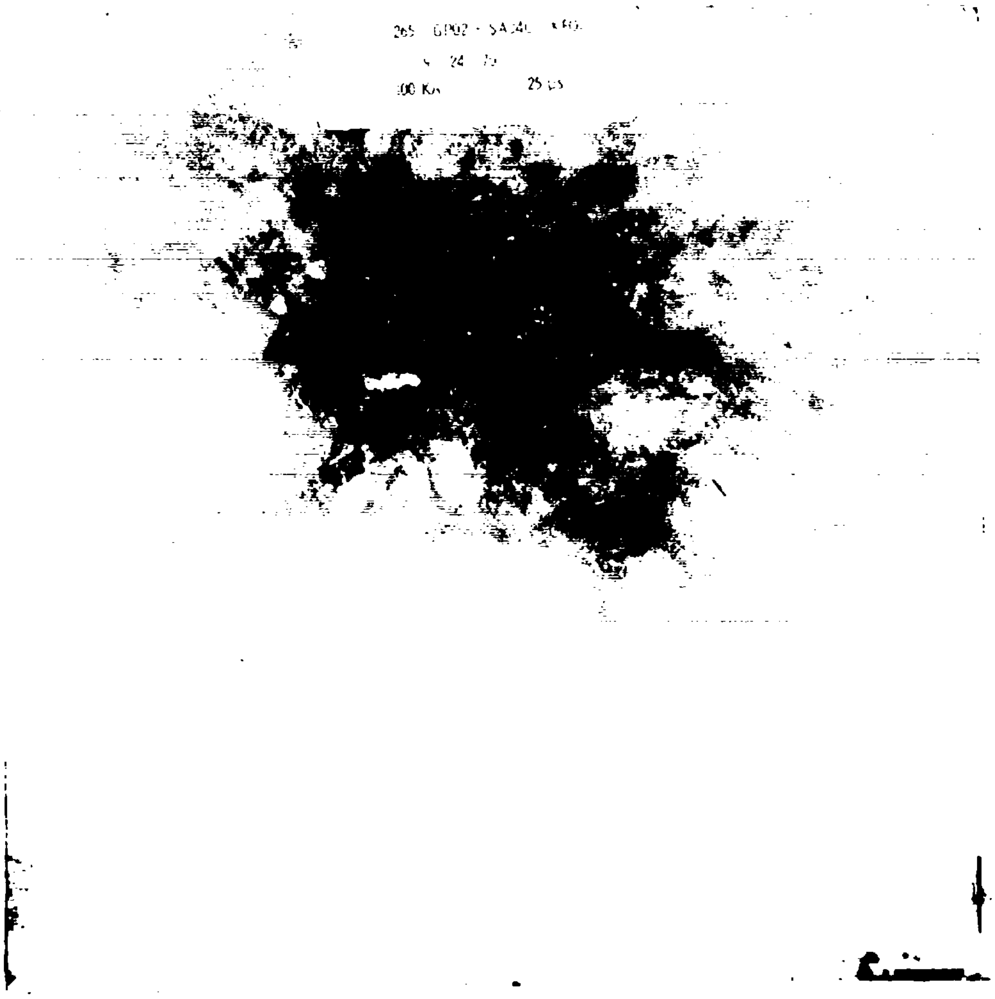


Figure 84   100 KA DISCHARGE DAMAGE TO SILVER COATED GRAPHITE EPOXY LAMINATE

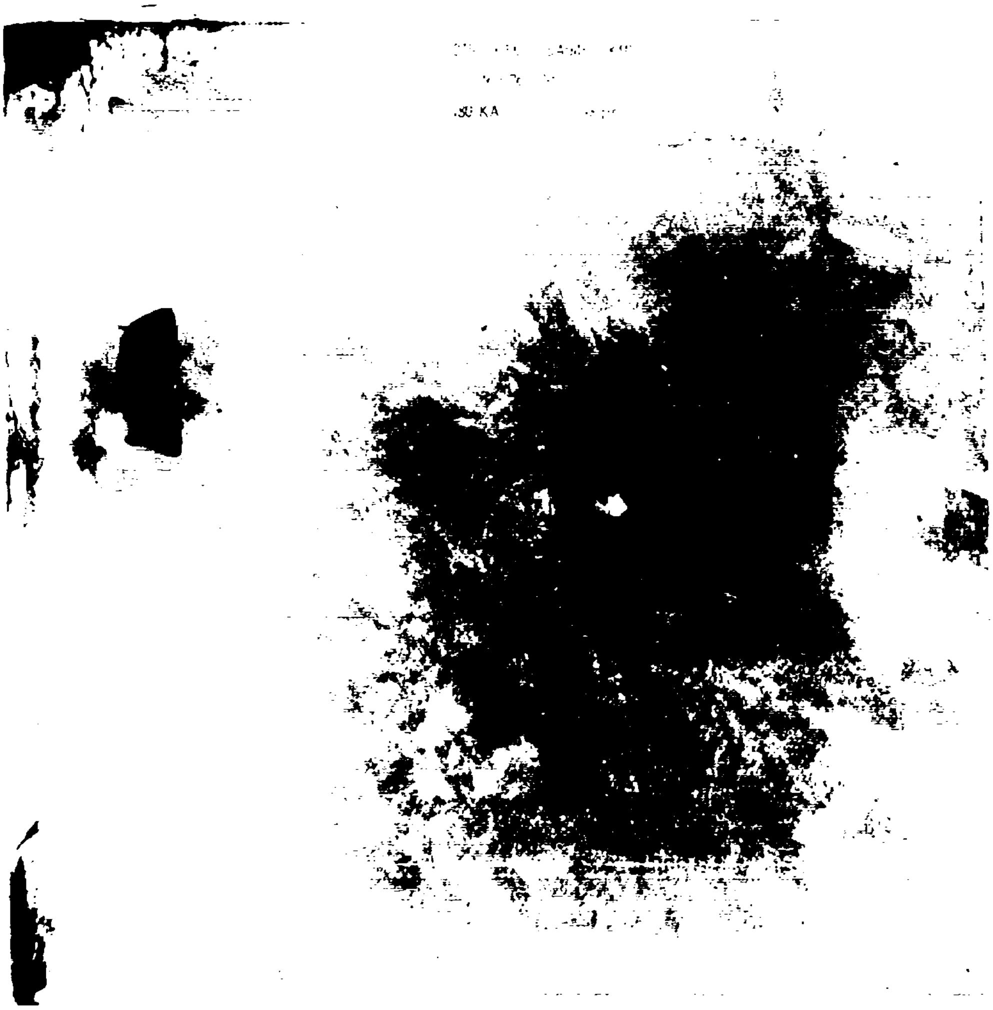


Figure 85 150 KA DISCHARGE DAMAGE TO SILVER COATED GRAPHITE EPOXY LAMINATE

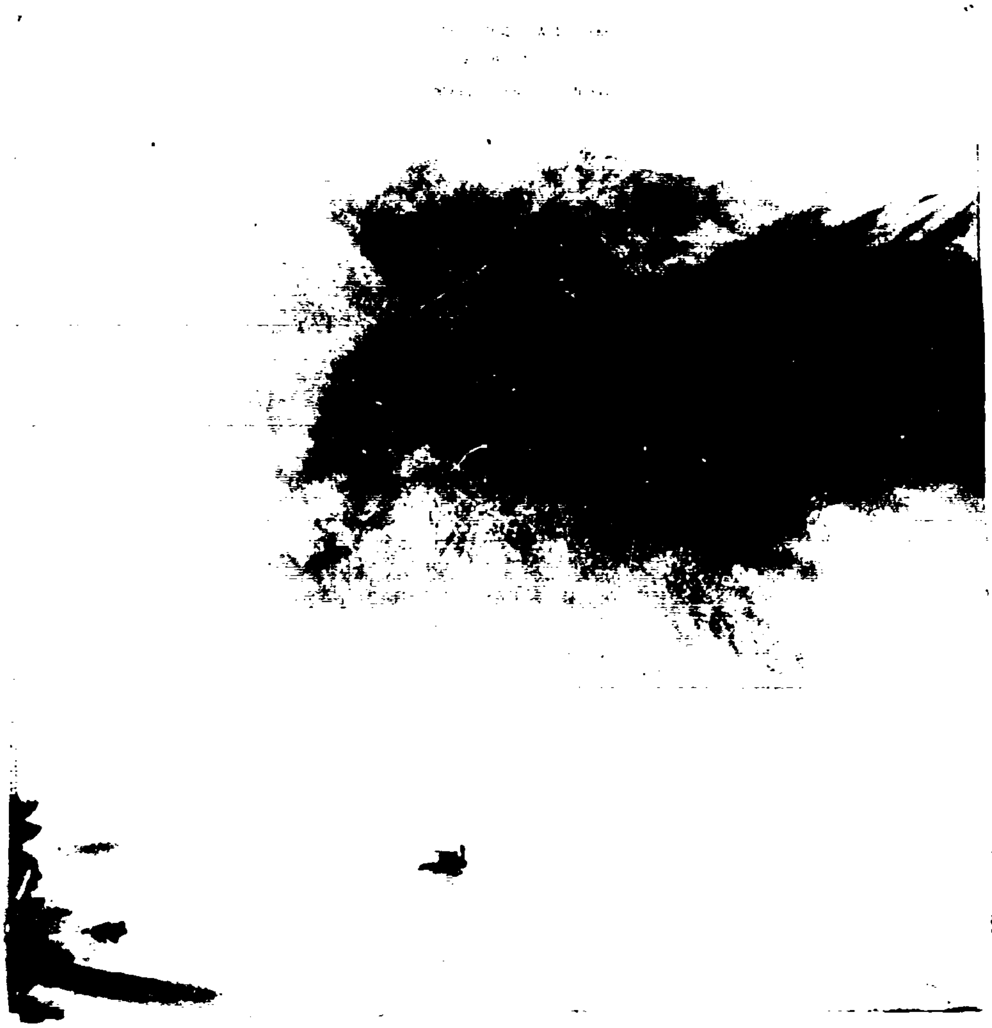


Figure 86 202 COULOMB TRANSFER DAMAGE TO A SILVER COATED GRAPHITE EPOXY LAMINATE

Finally, it is concluded that silver conductive coatings rely in part on shear bulk or thickness for coating protective efficiency. The employment of a 1-mil Kapton film underlayer in these coatings provided little additional protection qualities. Thus, this system apparently must maintain a thickness of at least 8 mils to provide the desired level of protection.

An interesting sidelight to these tests was revealed by an electron scanning microscope investigation of damage to boron filaments. A portion of the damage area is shown in Figure 87. Clearly visible is the filamentary nature and bidirectional character of the composite. The area shown is nearly free of resin as this was burned away by the electric current. The actual fracture of the filaments probably occurred as a result of rapid expansion of pyrolysis gases during the test.

A closer view of the composite is shown in Figure 88. The lower right hand side of this picture is a view of residual resin. The upper portion is of the scrim backing material which supports the preimpregnated filaments. The boron filaments clearly illustrate the boron sheath which surrounds the tungsten containing core. Three additional features are prominent in this view. The core of all of the filaments displays evidence of melting and resolidification. This is particularly obvious when compared with other views such as that in Figure 15b. While the filaments of Figure 15b are fractured, the core material is homogeneous. The core material of Figure 88 is not homogeneous, but shows distinct grain boundaries. These are more clearly illustrated in Figure 89. In this view of the core, the black area represents the boron sheath while the lighter area is the 0.0005-inch diameter core. Clearly visible are the grain boundaries in the core section. Additionally, both the lack of a grain structure at the edge of the core and the darker shading of this section indicate this material is different in its chemical nature than that of the interior portion of the core. This region is known to be boron rich, which accounts for its different behavior (7). The thickness of the boron rich portion of the core was determined from this photograph to be nearly 0.00005 inches (1.2 microns). This is in good agreement with electron microprobe X-ray analysis which reported a boron rich region 2 to 3 microns thick (7).

Another prominent feature of Figure 88 is the interior crack displayed by the filament on the left side. This flaw is not visible from the outside of the filament. Finally, all of the filaments display a series of holes which are generally near their outer boundaries although some of the filaments have holes nearer their centers. These are more prominently displayed in Figure 90. This shows the holes to be deep and of non-uniform cross-section. Additionally, an unidentified sheath exists about the filaments. This too is very porous.

These filament flaws undoubtedly lead to poor structural performance and the loss of strength and modulus of the filaments. It appears probable that these flaws are inherent in the material and are not due to lightning currents. This is because the void areas do not display an indication of the cracking which would accompany melting or vaporization due to joule heating.

Figure 87 SEM VIEW OF DAMAGED BORON FILAMENTS

Figure 88 [illegible]

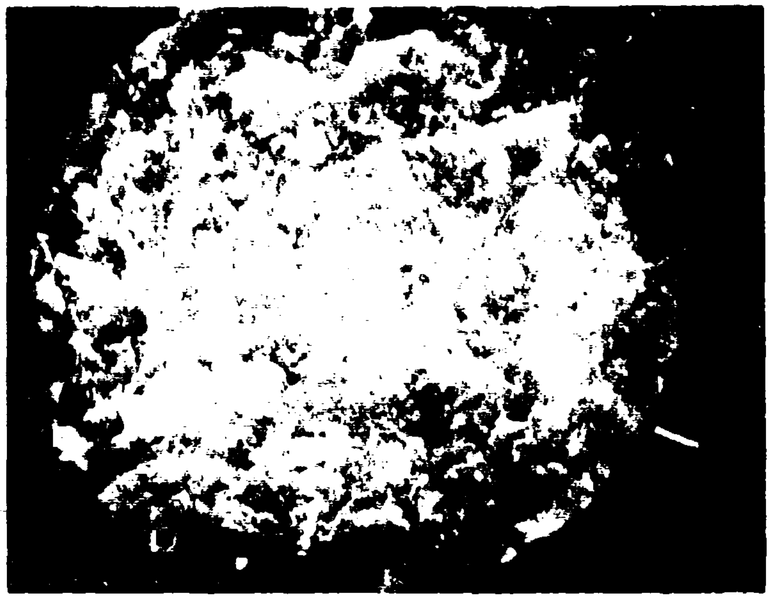


Figure [illegible] SEM VIEW OF DAMAGED BORON FILAMENTS

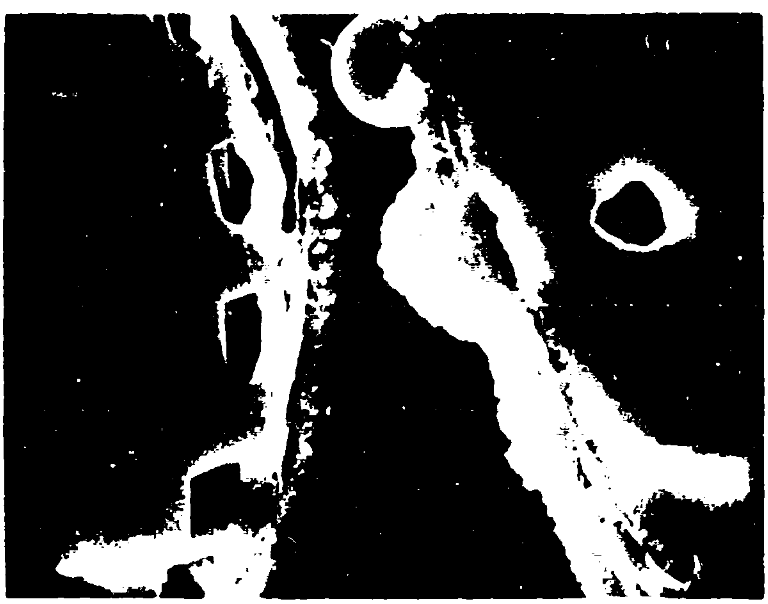


Figure [illegible] SEM VIEW OF DAMAGED BORON FILAMENTS

5.3 ELECTROMAGNETIC MEASUREMENTS

Measurements of the electromagnetic shielding capability of the advanced composite were conducted. Panels were tested for H-field insertion loss as a function of frequency as shown in the setup of Figure 91. The test coils are small enough to be regarded as magnetic dipoles and thus permit calculation of results for uniform sheets of material of known thickness and conductivity. These calculations have been verified by test. The dynamic range of measurement is limited by the size of panel available; "fringing" occurs around the edge of the test sheet at higher frequencies, i.e., insertion loss will then also depend on panel size. No measurements were made above frequencies at which fringing occurred on the test panels.

From the test results, the following conclusions were drawn.

A. Uncoated boron fiber panels have no intrinsic shielding effectiveness.

B. Uncoated graphite panels have slight shielding effectiveness, in conformance with measured conductivity.

C. Of the coatings tested, fine mesh aluminum fabric, aluminum foil, flame spray aluminum, and copper wire fabric are reasonably effective, in descending order. Potassium nitrate pigmented epoxy, silver pigmented epoxy, aluminum filled polyurethane paints and coarse aluminum mesh were ineffective.

Measurements of the induced voltage in an individual fiber due to the high current component discharge was also conducted. A total of six panels, three each of boron and graphite, were tested; these panels consisted of panels which were uncoated, coated with aluminum knitted wire mesh, and coated with aluminum foil. The knitted mesh had a 3-mil diameter wire with a mesh density of 13 by 24 and the aluminum foil was 1-mil thick.

Because of the practical difficulties of instrumenting a single boron or graphite fiber, a 28 gage insulated copper wire was laid in the laminate along the 12-inch dimension to simulate a single fiber. The leads were connected to a load resistor equivalent to the total resistance of a fiber and the output of the resistor was then connected to the battery operated Tektronix 432 oscilloscope to record the measured induced voltage. It is believed that this simulation is adequate because the induced voltage on a conductor due to resistive coupling in a uniform field is independent of the diameter of the wire.

The tests on uncoated substrates and panels coated with aluminum knitted wire mesh were unsuccessful. All the instrumented wires were vaporized due to the highly concentrated conduction current, i.e., the conduction current largely flowed through the copper wire instead of uniformly passing through all fibers. Only the aluminum foil coated substrate yielded results. It was found that induced voltage on a single

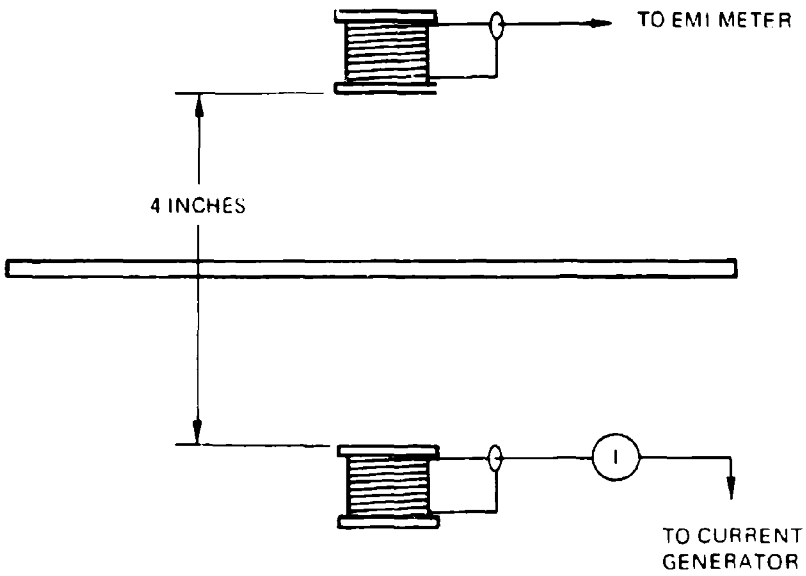


Figure 91 LABORATORY SETUP FOR EMI MEASUREMENT

fiber in a boron substrate was about 400 volts peak-to-peak, in a graphite substrate, 300 volts peak-to-peak both at a discharge current of 70 KA.

According to the results from Reference 7, the dynamic impedance of a 5-inch boron fiber varies from 1000 ohms to 2700 ohms based on the current amplitude and the static resistance is about 550 ohms. From this data and the above induced voltage test results, it can be extrapolated that the induced rms current on a single boron fiber with a 200 KA discharge will not be higher than 1.4 amp. The same extrapolation applied to graphite fibers yields the result that the maximum induced rms current on a single graphite fiber is approximately 7 ma at a 200 KA discharge.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

A parametric study has been completed on lightning protection requirements for boron-epoxy and graphite-epoxy laminates. Damage mechanisms have been identified and protective coating systems have been developed and tested.

Boron filament and graphite fiber reinforced plastics are very susceptible to lightning damage. Damage to boron filaments is of two types: (a) at low current levels, the filaments are not visibly damaged but are weakened, probably due to thermal stresses at the tungsten/boron interface; and (b) at high current levels the tungsten containing core behaves as an exploding wire and ruptures the filaments from within. Damage to graphite composites is of a different nature. As the fibers conduct electrical currents, they are subject to joule heating. This causes resin pyrolysis at the fiber-matrix interface and destroys the fiber-matrix bond. The explosive expansion of the pyrolysis gases causes delamination.

Numerous tests of potential lightning protective coatings for boron fiber and graphite fiber reinforced plastics have shown that successful coatings provide one of the following:

A. A surface with good electrical and thermal conductivities to divert the high energy from a lightning strike.

B. A conductive surface and a high dielectric underlayer to yield a surface flashover for the lightning arc without an electrical breakdown between the arc and the fibers.

C. An electrically resistive surface with a high dielectric strength underlayer, and attached metal members. The coating-dielectric system prevents attachment of the arc to the reinforcing fibers, while the metal members lead the current to the ground.

All of the successful coating systems can be identified as belonging to one of these categories. Coating concepts which were not successful, generally failed because they did not provide a low energy pathway to electrical ground.

Damage to composites by lightning discharge can be of two types:

A. High coulomb transfer tests yield highly localized damage. This damage is primarily thermal and is due to the attachment of a long duration high temperature arc. The high surface temperature due to joule heating will be a problem if the composite is used in a temperature sensitive area such as fuel tank skin.

B. High current discharges usually cause electrical damage over a wider area. This is due to the high potential levels which cause the discharge currents to spread out from the contact point. Mechanical damage, a by-product from the shock wave, will be reduced with a heavier structure.

This same type of damage is incurred by the coatings.

Specific coating comments include:

A. Continuous metal foils are one means of protecting high modulus composites from lightning damage. Aluminum is the best material for this purpose. A one mil foil provides good protection at moderate discharges (ca 100 KA) but a 6 mil foil is necessary for higher level discharges.

B. Of the metal pigmented paints, only silver pigments provide the conductivity necessary for lightning protection. The silver pigmented coating must be at least 6 mils to 8 mils thick. Thinner, 4-mil, coatings even with 1-mil Kapton dielectric underlayers, are not sufficient; however, this coating system provides some protection against low level discharge.

C. Flame and plasma sprayed aluminum behave much like continuous metal foils. This unique surface does tend to enhance surface flashover for these coatings as coating puncture does not occur as with continuous foils. These systems are required to be at least 4 mils thick for moderate discharge levels, but 6-8 mils are required for high discharge levels.

D. Low conductive coatings can provide excellent lightning protection when certain electrical properties are provided. Inorganic salt pigmented epoxies have performed well in this regard. The coating incorporates continuous metal strips as expendable conductive members to carry current to electric ground.

E. Woven wire fabrics and knitted wire mesh provide the most efficient lightning protection system. These materials must provide a metal thickness comparable of at least 1.5 mils of aluminum foil by weight.

Uncoated boron/epoxy or graphite/epoxy do not provide any electromagnetic shielding. Coated substrates, except fine woven wire fabrics and foil coatings, do not provide any significant EM shielding. Due to this poor EM shielding property of the uncoated or coated substrate, an induced current in a filament can be expected; however, the extrapolated test data indicate the induced currents will not degrade the high modulus fibers.

Although the success of the investigation reported herein surpasses pre-contract predictions, there are several aspects of protective coating usage that may warrant attention. First, further consideration should be given to optimization of the coating systems for operational use in terms of cost, weight, environmental compatibility and ease of application. Secondly, an analysis is recommended of the impact of the protective coatings on all aircraft electrical and electronic systems to ensure that safety, reliability, economy, and operational performance are not compromised. Additionally, it is recommended that the electrical tests be expanded to include swept strokes and restrikes to more nearly simulate a natural lightning environment, thereby improving the analysis criteria.

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APPENDIX

GENERAL DESCRIPTION OF THE TEST PANELS

001-FG01-AF02C-0000 Figure A-1 July 28, 1969
A 3M spray adhesive #77 was used to bond a 2-mil aluminum foil to this fiberglas panel with no undercoating. An 80 KA discharge with a pulse of 40 μs was directed to this coated panel.

No damage to the substrate was observed.

002-FG02-AF03C-0000 Figure A-1 July 28, 1969
A 3M spray adhesive #77 was used to bond a 3-mil aluminum foil to this fiberglas panel with no undercoating. An 80 KA discharge with a pulse of 40 μs was directed to this coated panel.

No damage to the substrate was observed.

003-FG03-AF03C-0000 Figure A-1 July 29, 1969
A 3M spray adhesive #77 was used to bond a 3-mil aluminum foil to this fiberglas panel with no undercoating. Two 90 KA discharges were directed to this coated panel with a pulse duration of 40 μs.

No damage to the substrate was observed.

004-FG04-AF02C-0000 Figure A-1 July 29, 1969
A 3M spray adhesive #77 was used to bond a 2-mil aluminum foil to this fiberglas panel with no undercoating. Two 90 KA discharges with a pulse duration of 40 μs were directed to this coated panel.

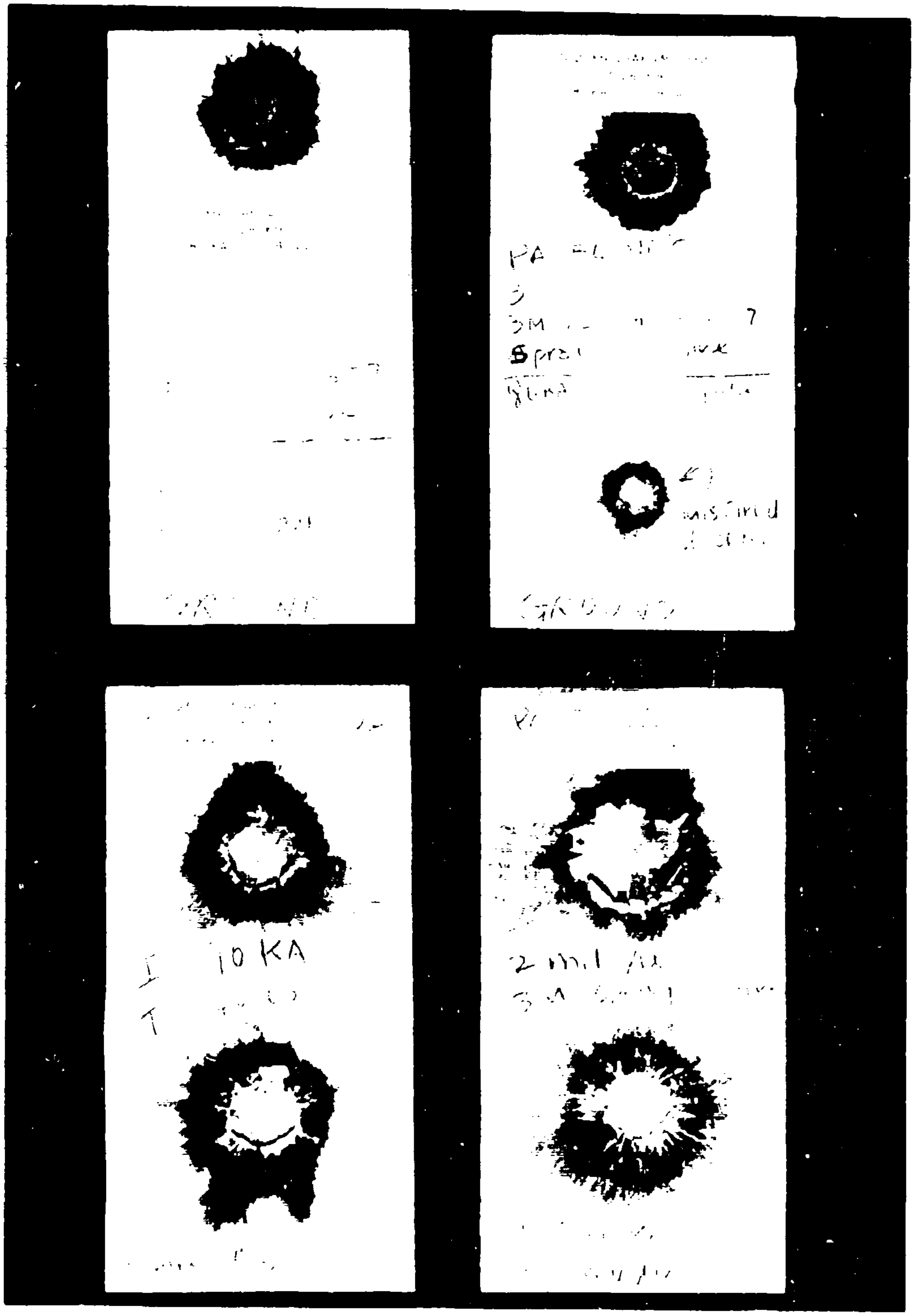
No damage to the substrate was observed.

006-FG06-AF01C-0000 Figure A-2 August 6, 1969
A 3M spray adhesive #77 was used to bond a 1-mil aluminum foil to this fiberglas panel with no undercoating. A 110 KA discharge with a pulse duration of 25 μs was directed to this coated panel.

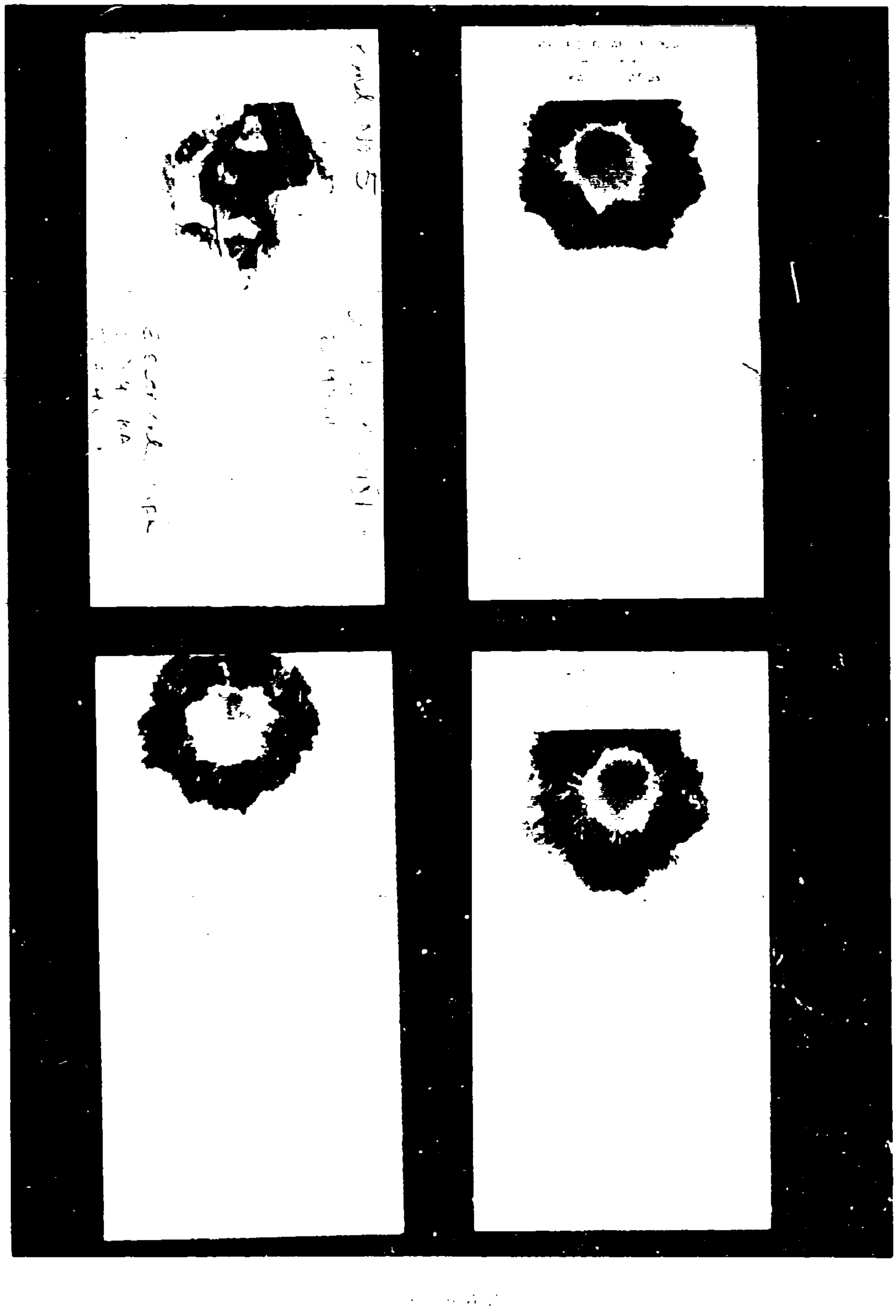
No damage to the substrate was observed; part of the foil along the panel edge was peeled.

007-FG07-AF01C-0000 Figure A-2 August 6, 1969
A 3M spray adhesive #77 was used to bond a 1-mil aluminum foil to this fiberglas panel with no undercoating. A 110 KA discharge with a pulse duration of 25 μs was directed to this coated panel.

No damage to the substrate was observed.



10 KA
2 mil Al
misfired
GROUND



008-FG08-AF01C-KF01 Figure A-2 August 6, 1969

A 3M spray adhesive #77 was used to bond a 1-mil aluminum foil to this fiberglas panel with an undercoating of 1 mil Kapton film. A 110 KA discharge with a pulse duration of 25 μs was directed to this coated panel.

No damage to the substrate was observed; however, part of the foil along the edge was peeled.

009-FG09-AF01C-KF01 Figure A-3 August 6, 1969

A 3M spray adhesive #77 was used to bond a 1-mil aluminum foil to this fiberglas panel with an undercoating of a 2-mil Kapton film. A 110 KA discharge with a pulse duration of 25 μs was directed to this coated panel.

No damage to the substrate was observed; however, part of the foil along the edges was peeled.

010-FG10-AF01C-KF02 Figure A-3 August 6, 1969

A 3M spray adhesive #77 was used to bond a 1-mil aluminum foil to this fiberglas panel with an undercoating of a 2-mil Kapton film. A 110 KA discharge with a pulse duration of 25 μs was directed to this coated panel.

No damage to the substrate was observed.

011-FG11-AF01C-KF02 Figure A-3 August 7, 1969

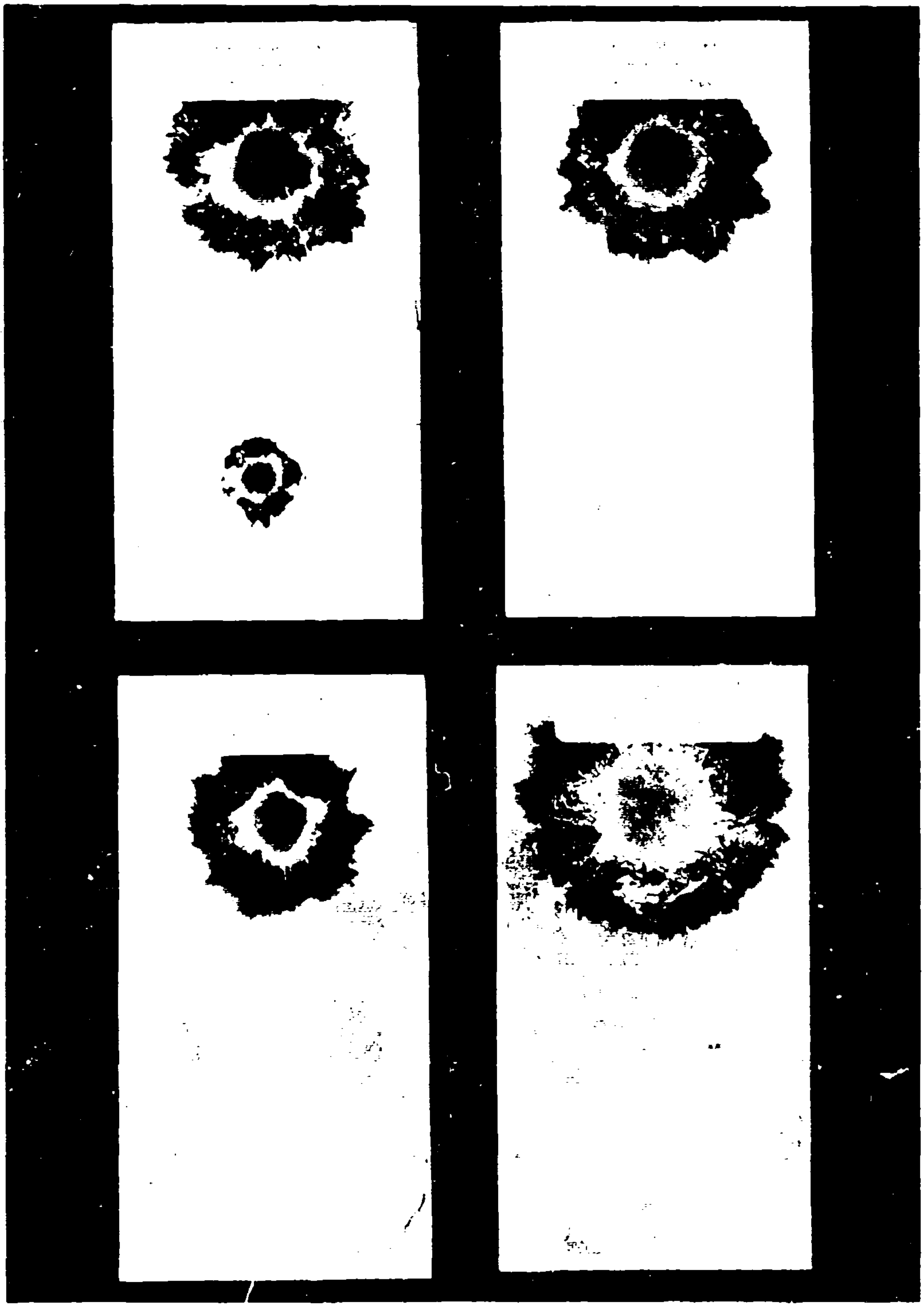
A 3M spray adhesive #77 was used to bond a 1-mil aluminum foil to this fiberglas panel with an undercoating of a 2-mil Kapton film. A 110 KA discharge with a pulse duration of 25 μs was directed to this coated panel.

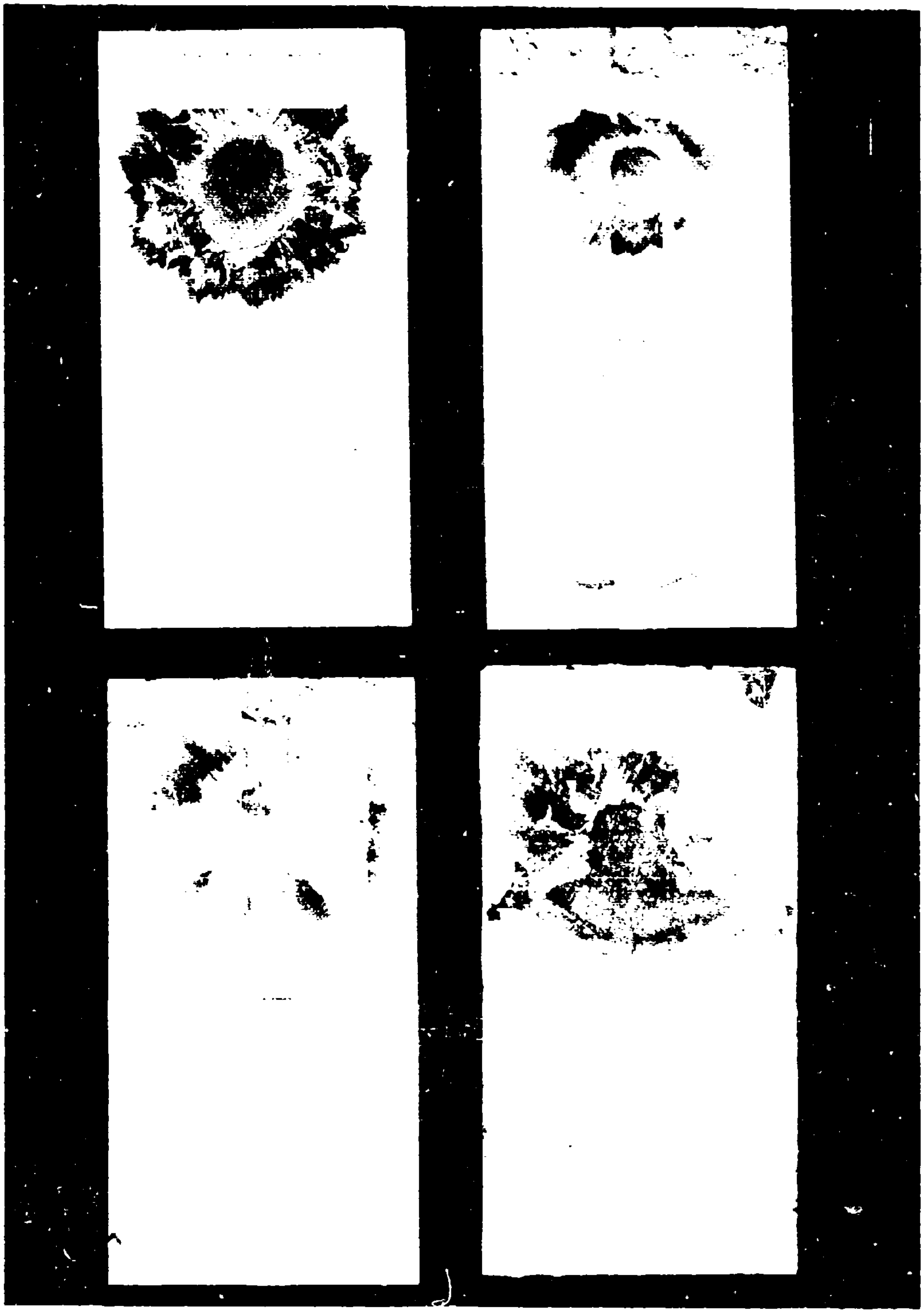
No damage to the substrate was observed.

012-FG12-AF01C-KF03 Figure A-3 August 7, 1969
013-FG13-AF01C-KF03 Figure A-4

A 3M spray adhesive #77 was used to bond a 1-mil aluminum foil to these two fiberglas panels with an undercoating of a 3-mil Kapton film. Two 110 KA discharges with a pulse duration of 25 μs were directed to these two identically coated panels.

No damage was observed on either substrate; however, part of the foil along the edges was peeled.





014-FG14-AF01P-0000 Figure A-4 August 7, 1969

An electrical aluminum tape of 1-mil thick and 1-inch wide was bonded to this fiberglas panel with no undercoating. A 110 KA discharge with a pulse duration of 25 μs was directed to the center tape.

No damage to the FG panel was observed; however, badly burned, bubbled and pitted tapes were evidenced at the overlapped taped area.

015-FG15-AF01P-0000 Figure A-4 August 7, 1969

An electrical aluminum tape of 1-mil thick and 1-inch wide was bonded to this fiberglas panel with no undercoating. A 110 KA discharge with a pulse duration of 25 μs was directed to the center tape.

No damage to the FG panel was observed; however, most of the tape was vaporized. Badly burned tapes were produced at the overlapped areas of tape.

016-BR01-AF01C-KF01 Figure A-4 August 25, 1969

A 1-mil-aluminum foil was adhesively bonded to this boron panel with a 1-mil Kapton film undercoating. The adhesive was epoxy, BMS 5-29. A 16 KV discharge was initiated to this coated panel; the discharge current had a peak amplitude of 87 KA with a risetime of 16 μs and a duration of 30 μs.

No visible damage to the substrate was observed; however, the foil was wrinkled and part of the foil along both edges was peeled off.

017-BR02-AF01C-0000 Figure A-5 August 25, 1969

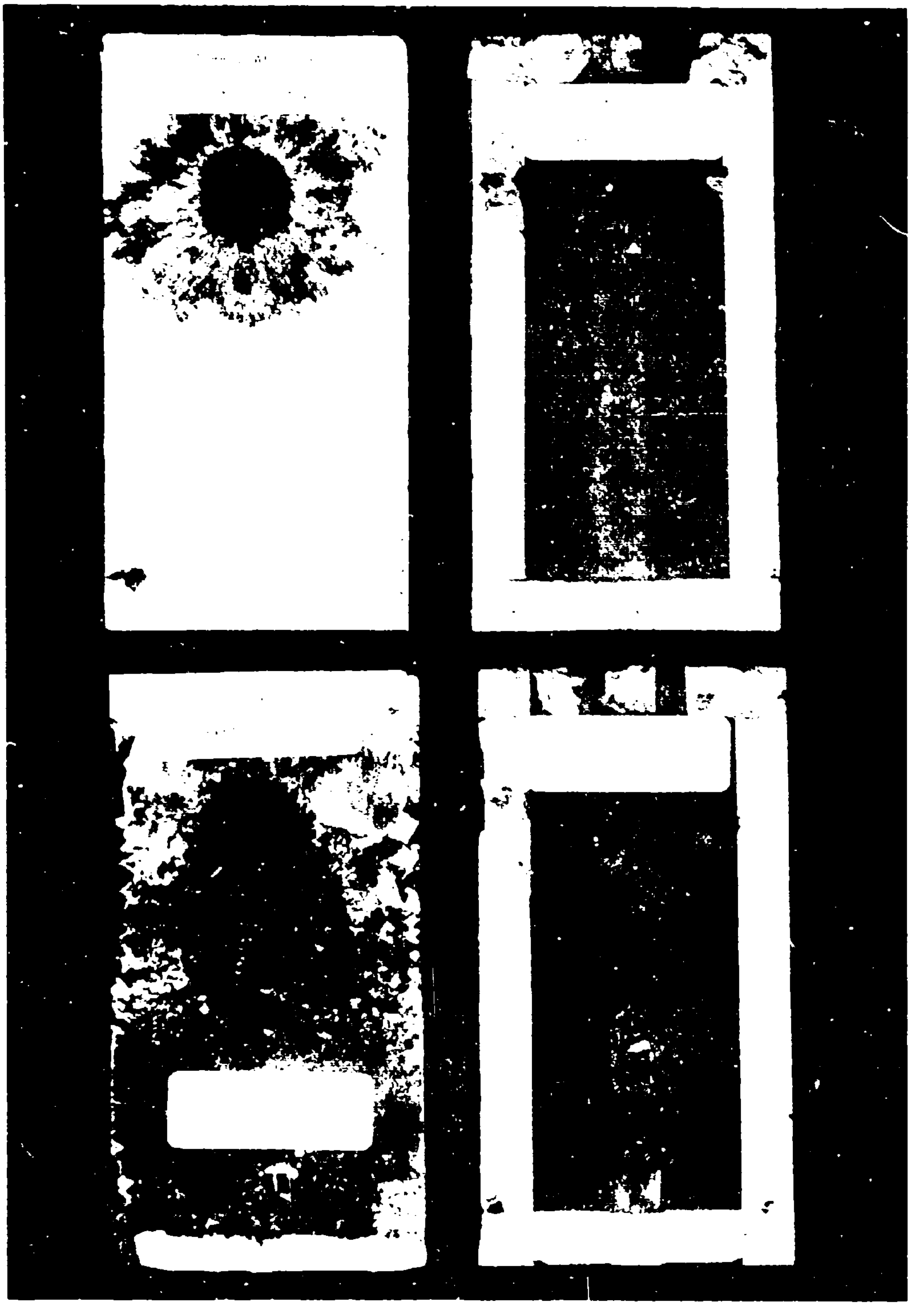
A 1-mil aluminum foil was integrally bonded to this boron panel with no undercoating. An 18 KV discharge was initiated to this coated panel; the discharge current had a peak amplitude of 100 KA with a risetime of 18 μs and a duration of 32 μs.

No visible damage to the substrate was observed; however, some burned spots of vaporized aluminum foil were shown and were probably due to resistive heating.

018-BR03-AF01P-0000 Figure A-5 August 25, 1969

An electrical aluminum tape of 1-mil thick and 1-inch wide was bonded to this boron panel with no undercoating. A 17 KV discharge was directed to this coated panel; the discharge current had a peak amplitude of 94 KA with a risetime of 18 μs and a duration of 32 μs.

No visible damage to the substrate was observed. However, the center tape was completely vaporized, the top tape (the tape on the end other than the grounded side) was severely burned and there was also very bad bubbling and pitting between the overlapped area of the tapes.



019-GP01-AF01C-0000 Figure A-5 August 25, 1969

A 1-mil aluminum foil was adhesively bonded to this graphite panel with no undercoating. The adhesive was an epoxy, BMS 5-29. Two discharges were directed to this coated panel. The first one had a 17 KV discharge, the discharge current had a peak amplitude of 94 KA with a risetime of 18 μs and a duration of 32 μs; no visible damage to the substrate was observed although the foil along both the edges was peeled. The second one was a 30 KV discharge with the crowbar switch disconnected. This exponentially decayed oscillating discharge current had a peak amplitude of 167 KA with a ringing frequency of 32 kHz; the substrate had a one-inch puncture hole.

020-GP02-AF01P-0000 Figure A-5 August 25, 1969

An electrical aluminum tape of 1-mil thick and 1-inch wide was bonded to this graphite panel with no undercoating. A 17 KV discharge was initiated to this coated panel; the discharge current had a peak amplitude of 94 KA with a rise time of 18 μs and a duration of 32 μs.

No visible damage to the substrate was observed. However, the center tape was completely vaporized, the top tape (the tape on the end other than the grounded side) was severely burned and there was also very bad bubbling and pitting between the overlapped area of tapes.

021-GP03-AF03C-0000 Figure A-6 August 25, 1969

A 3-mil aluminum foil was adhesively bonded to this graphite panel with no undercoating. The adhesive was epoxy, BMS 5-29. A 17 KV discharge was initiated to this coated panel; the discharge current had a peak amplitude of 94 KA with a risetime of 18 μs and a duration of 32 μs.

A slightly burned substrate surface was produced and most of the foil was wrinkled.

022-GP04-AF03-KF01 Figure A-6 August 25, 1969

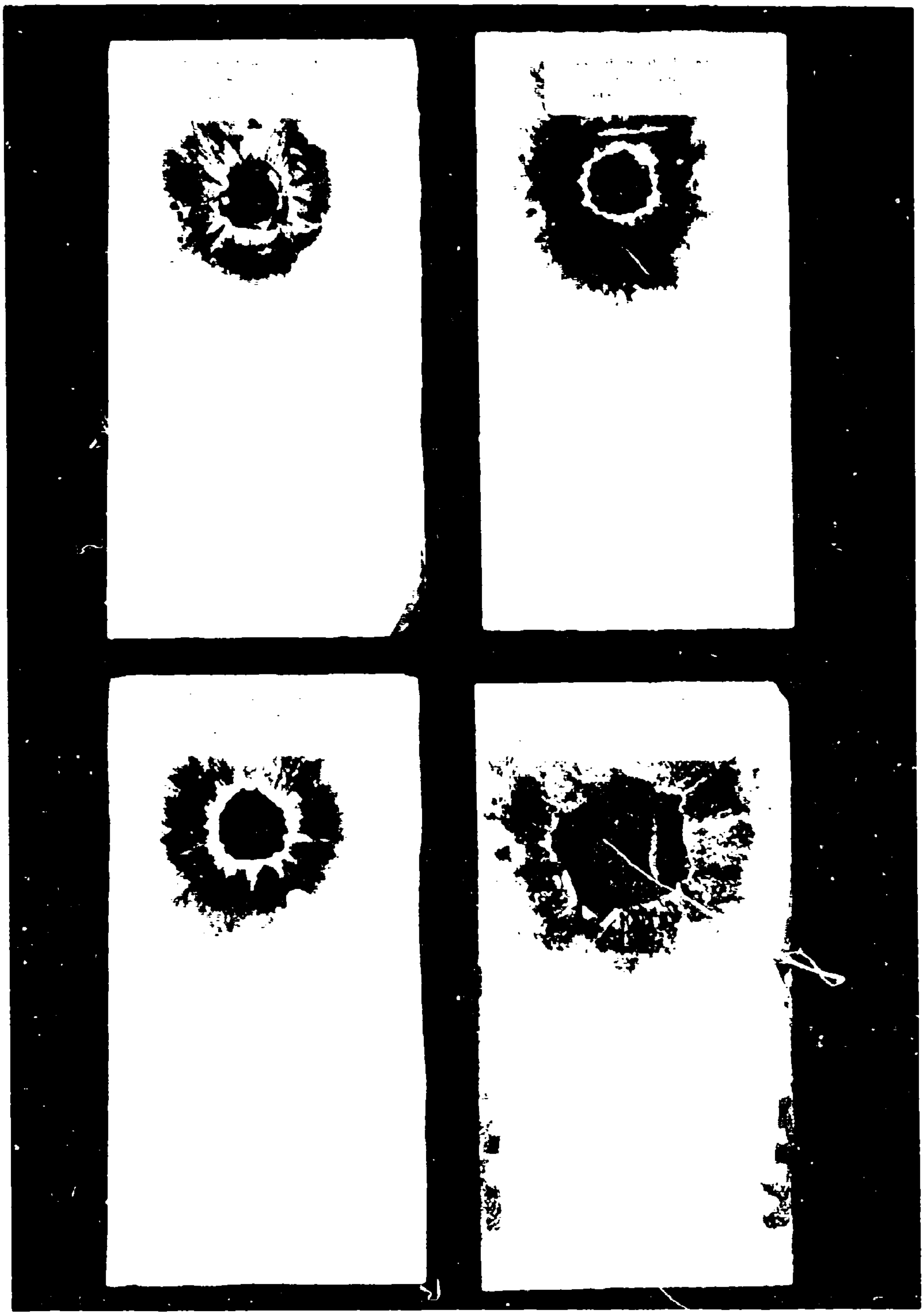
A 3M spray adhesive #77 was used to bond a 3-mil aluminum foil to this graphite panel with an undercoating of 1-mil Kapton film. A 17 KV discharge was initiated to this coated panel; the discharge current had a peak amplitude of 94 KA with a risetime of 16 μs and a duration of 30 μs.

A small visible burned mark on the Kapton film undercoating was observed.

023-GP05-AF03C-KF02 Figure A-6 August 25, 1969

A 3M spray adhesive #77 was used to bond a 3-mil aluminum foil to this graphite panel with an undercoating of a 2-mil Kapton film. A 17 KV discharge was directed to this coated panel; the discharge current had a peak amplitude of 94 KA with a risetime of 16 μs and a duration of 30 μs.

No visible damage to the substrate was observed.



024-GP06-AF01C-KF01 Figure A-6 August 25, 1969

A 3M spray adhesive #77 was used to bond a 1-mil aluminum foil to this graphite panel with an undercoating of a 1-mil Kapton film. Because of the poor bonding process, there were wrinkles on the surface of the foil before the coated panel was tested. A 17 KV discharge was directed to this panel; the discharge current had a peak amplitude of 94 KA with a risetime of 16 μs and a duration of 30 μs.

No visible damage to the substrate was observed; however, part of the foil along both the edges was peeled off.

025-GP07-AF01C-KF03 Figure A-7 August 26, 1969

A 3M spray adhesive #77 was used to bond a 1-mil aluminum foil to this graphite panel with an undercoating of a 3-mil Kapton film. A 17 KV discharge was directed to this coated panel; the discharge current had a peak amplitude of 94 KA with a risetime of 16 μs and a duration of 30 μs.

A slightly burned mark on the Kapton film surface was produced and part of the foil along both edges was peeled off.

026-GP08-AF03C-KF03 Figure A-7 August 26, 1969

A 3M spray adhesive #77 was used to bond a 3-mil aluminum foil to this graphite panel with an undercoating of a 3-mil Kapton film. A 20 KV discharge was initiated to this coated panel; the discharge current had a peak amplitude of 123 KA with a risetime of 16 μs and a duration of 30 μs.

The graphite panel was cracked.

027-GP09-AF01C-KF02 Figure A-7 August 26, 1969

An epoxy adhesive, BMS 5-29, was used to bond a 1-mil aluminum foil to this graphite panel with an undercoating of a 2-mil Kapton film. An 18 KV discharge was initiated to this coated panel; the discharge current had a peak amplitude of 100 KA with a risetime of 16 μs and a duration of 30 μs.

A small burned spot on the Kapton film surface was produced, and burned and peeled aluminum foil was also observed.

028-BR04-AF03C-KF03 Figure A-7 August 26, 1969

A 3M spray adhesive #77 was used to bond a 3-mil aluminum foil to this boron panel with an undercoating of a 3-mil Kapton film. An 18 KV discharge was directed to this coated panel; the discharge current had a peak amplitude of 100 KA with a risetime of 16 μs and a duration of 30 μs.

No visible damage to the substrate was observed.

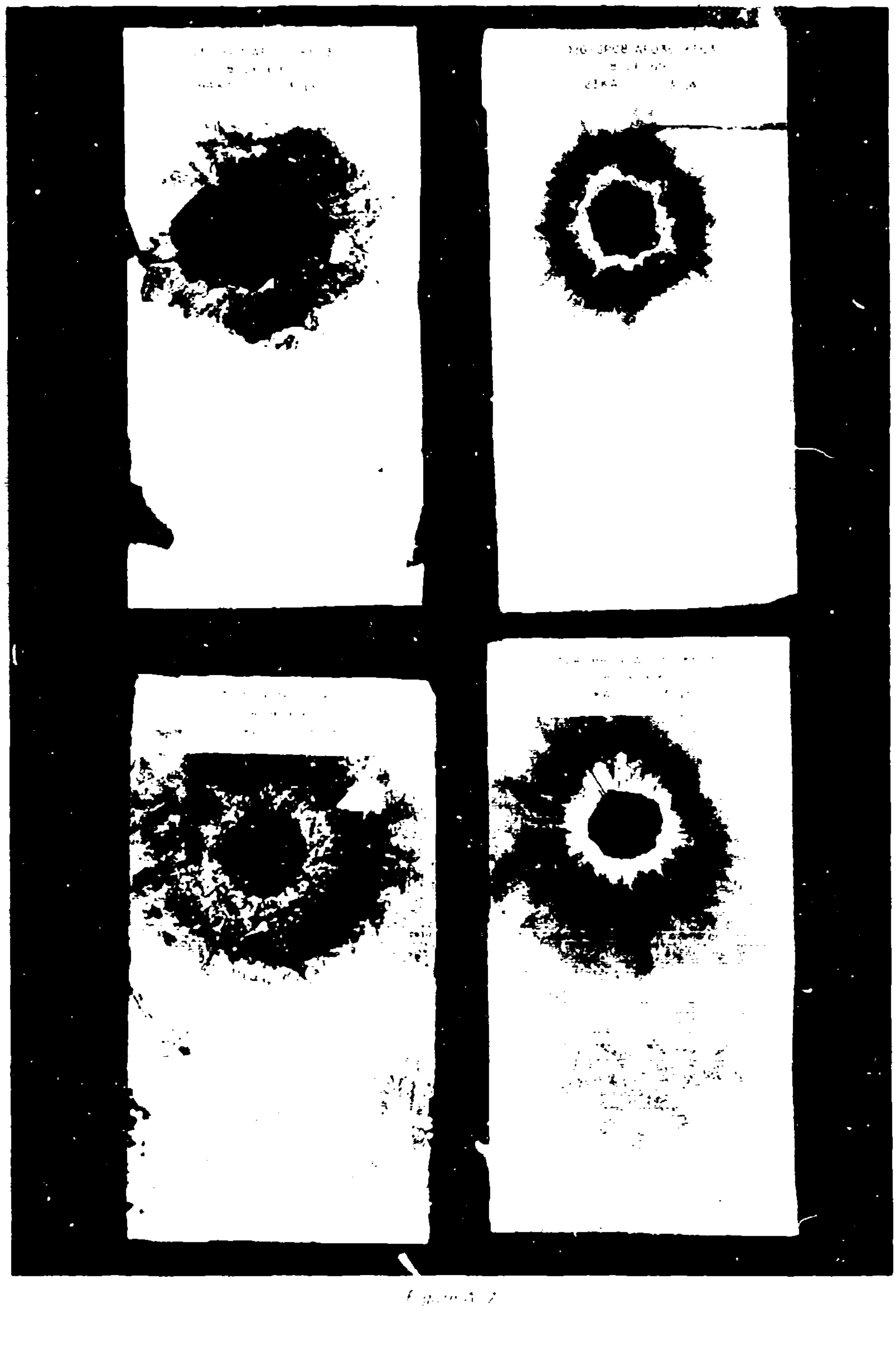


Figure A-2

029-BR05-AS04C-0000 Figure A-8 August 26, 1969

This boron panel was coated with a 4-mil flame-sprayed aluminum paint with no undercoating. An 18 KV discharge was initiated to this coated panel; the discharge current had a peak amplitude of 100 KA with a rise-time of 16 μs and a duration of 30 μs.

No visible damage to the substrate was observed; however, many burned marks on the aluminum paint surface were produced.

030-BR06-AS04C-0000 Figure A-16 August 26, 1969

This boron panel was coated with 4-mil flame-sprayed aluminum with no undercoating. There were two discharges directed to this coated panel. The first one was an 18 KV discharge which had a peak amplitude of 100 KA with a rise time of 16 μs and a duration of 30 μs.

No visible damage to the substrate was observed although many burned marks on the aluminum paint surface were produced.

The second discharge had a 29 KV peak with the crowbar switch disconnected. This exponentially decayed oscillating discharge current had a peak amplitude of 160 KA with a ringing frequency of 32 kHz.

The substrate was severely damaged and the aluminum paint surface was also badly burned.

031-BR07-AF03C-KF02 Figure A-8 August 26, 1969

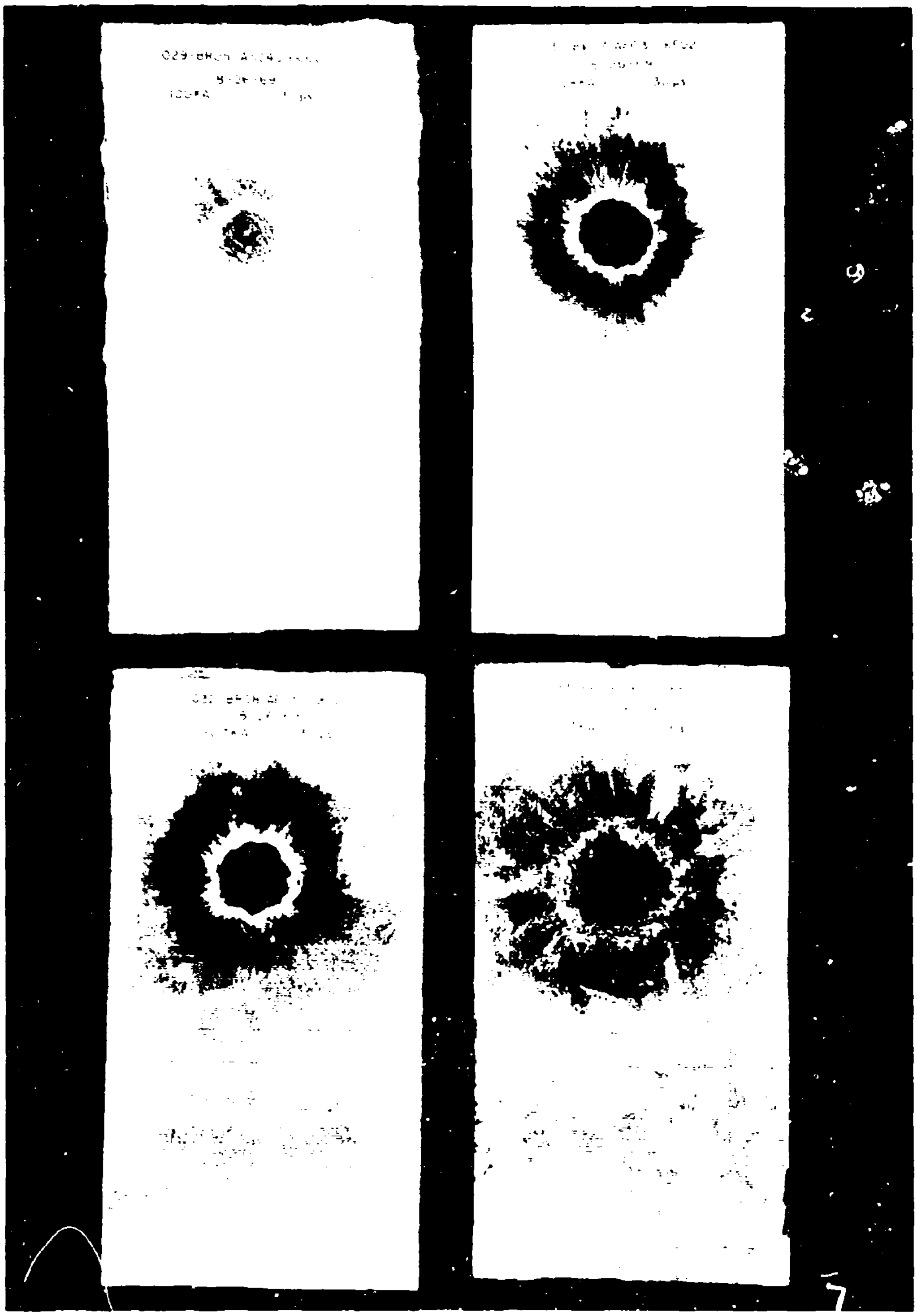
A 3M spray adhesive #77 was used to bond a 3-mil aluminum foil to this boron panel with an undercoating of a 2 mil Kapton film. A 19 KV discharge was initiated to this coated panel; the discharge current had an amplitude of 109 KA with a risetime of 16 μs and a duration of 30 μs.

The substrate was cracked which could have been caused by the high pressures generated by the stroke, or by a collision between the discharge probe and the panel; however, the surface of the Kapton film undercoating was not damaged.

032-BR08-AF03C-0000 Figure A-8 August 26, 1969

A 3M spray adhesive #77 was used to bond a 3-mil aluminum foil to this boron panel with no undercoating. An 18 KV discharge was directed to this coated panel; the discharge current had a peak amplitude of 107 KA with a risetime of 16 μs and a duration of 30 μs.

The substrate was cracked which could have been caused by the high pressures generated by the stroke, or by a collision between the discharge probe and the panel; however, the Kapton film was not damaged.



033-BR09-AF01C-KF03 Figure A-8 August 26, 1969

An epoxy adhesive, BMS 5-29, was used to bond a 1-mil aluminum foil to this boron panel with an undercoating of a 3-mil Kapton film. An 18 KV discharge was initiated to this coated panel; the discharge current had a peak amplitude of 107 KA with a risetime of 12 μs and a duration of 26 μs.

No damage to the substrate was observed.

034-FG16-AF02C-KF03 Figure A-9 August 26, 1969

A 3M spray adhesive #77 was used to bond a 2-mil aluminum foil to this fiberglas panel with an undercoating of a 3-mil Kapton film. The crowbar switch was disconnected from the simulator, a 30 KV discharge was then directed to this coated panel and the exponentially decayed oscillating discharge current had a peak amplitude of 160 KA with a ringing frequency of 33 kHz.

No damage to the fiberglas substrate was observed.

035-FG17-AF02C-KF03 Figure A-9 August 27, 1969

A 3M spray adhesive #77 was used to bond a 2-mil aluminum foil to this fiberglas panel with an undercoating of a 3-mil Kapton film. An 18 KV discharge was directed to this coated panel; the discharge current had a peak amplitude of 100 KA with a risetime of 14 μs and a duration of 26 μs.

No visible damage to the fiberglas substrate was observed.

036-BR10-AF01C-0000 Figure A-9 August 27, 1969

A 1-mil aluminum foil was integrally bonded to the boron panel with no undercoating. An 18 KV discharge was initiated to this coated panel; the discharge current had an amplitude of 100 KA with a risetime of 14 μs and a duration of 26 μs.

A visible crack was observed on the back side of the substrate, and burned marks of the aluminum foil along both the edges were also shown; however, the front surface of the substrate was found to have no damage.

037-BR11-AF01C-KF02 Figure A-9 August 27, 1969

The epoxy adhesive, BMS 5-29, was used to bond a 1-mil aluminum foil to this boron panel with an undercoating of a 2-mil Kapton film. An 18 KV discharge was directed to this coated panel; the discharge current had an amplitude of 100 KA with a risetime of 14 μs and a duration of 26 μs.

No damage to the substrate was observed; however, part of the foil was burned and peeled.

038-BR11-AF03C-KF01 Figure A-10 August 27, 1969

The epoxy adhesive, BMS 5-29, was used to bond a 1-mil aluminum foil to this boron panel with an undercoating of a 2-mil Kapton film. An 18 KV discharge was directed to this coated panel; the discharge current had an amplitude of 100 KA with a risetime of 14 μs and a duration of 26 μs.

No damage to the substrate was observed.

039-BR13-00000-KF01 Figure A-10 August 27, 1969

This boron panel had no protective coating. A 1-mil Kapton film was between the first and second fiber plies which provided the outer ply as a sacrificial layer. An 18 KV discharge was initiated to this coated panel; the discharge current had an amplitude of 43 KA with a risetime of 14 μs and a duration of 44 μs.

The substrate was punctured with several holes, burned marks were shown all over the front surface, and a few burned marks were also shown on the back side of the substrate.

040-BR14-00000-0000 Figure A-10 August 27, 1969

This was an uncoated boron panel. An 18 KV discharge was directed to the panel; the discharge current had an amplitude of 43 KA with a risetime of 14 μs and a duration of 44 μs.

The substrate was severely damaged, burned marks were shown all over the front surface and fewer burned marks were shown on the back side of the substrate.

041-BR15-AF01C-0000 Figure A-10 September 16, 1969

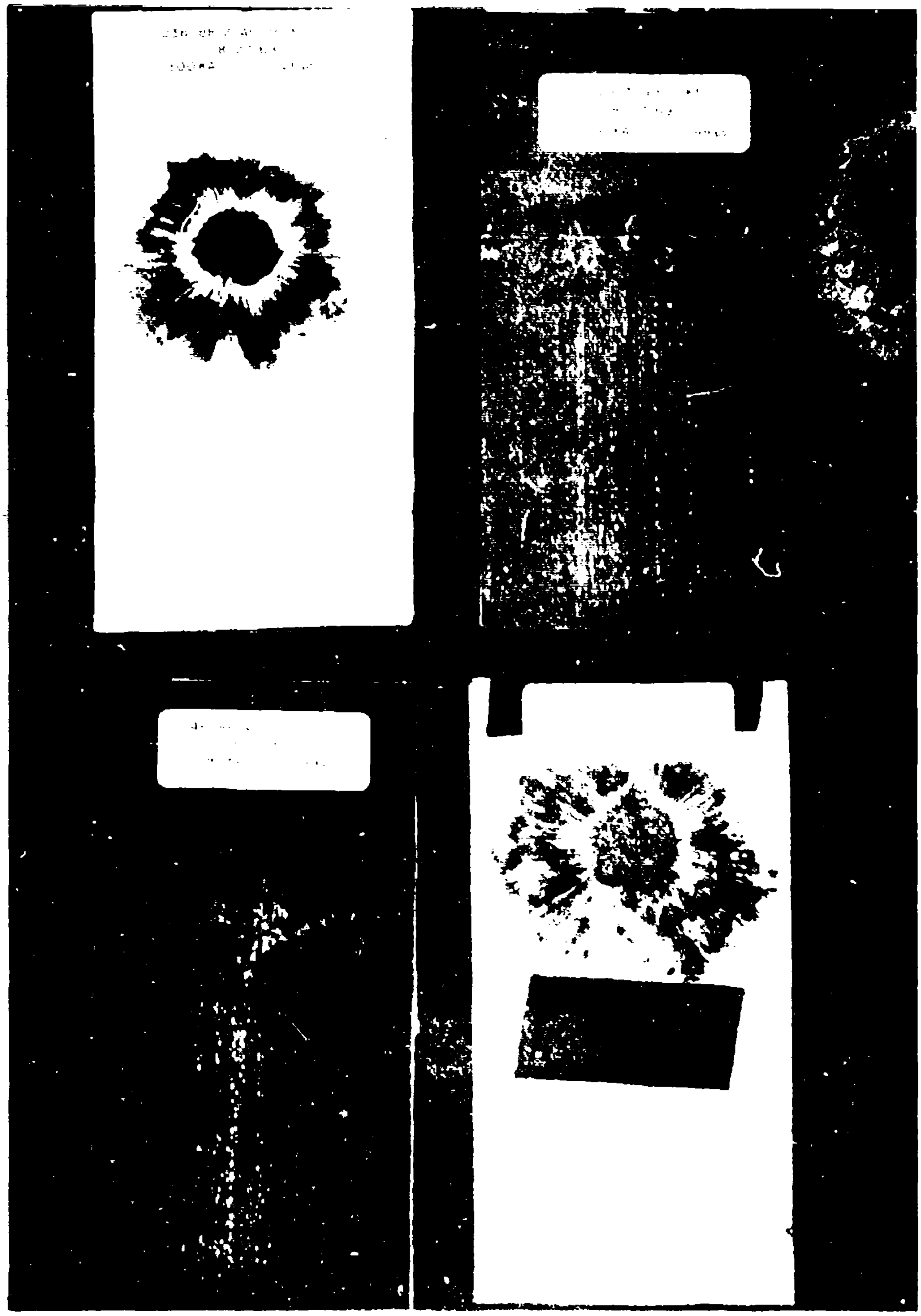
A 1-mil aluminum foil was integrally bonded to this boron panel on the scrim cloth side of the tape and no undercoating was applied. The fibers of this boron panel were unidirectional. An 18 KV discharge was directed to this coated panel; the discharge current had an amplitude of 95 KA with a risetime of 15 μs and a duration of 28 μs.

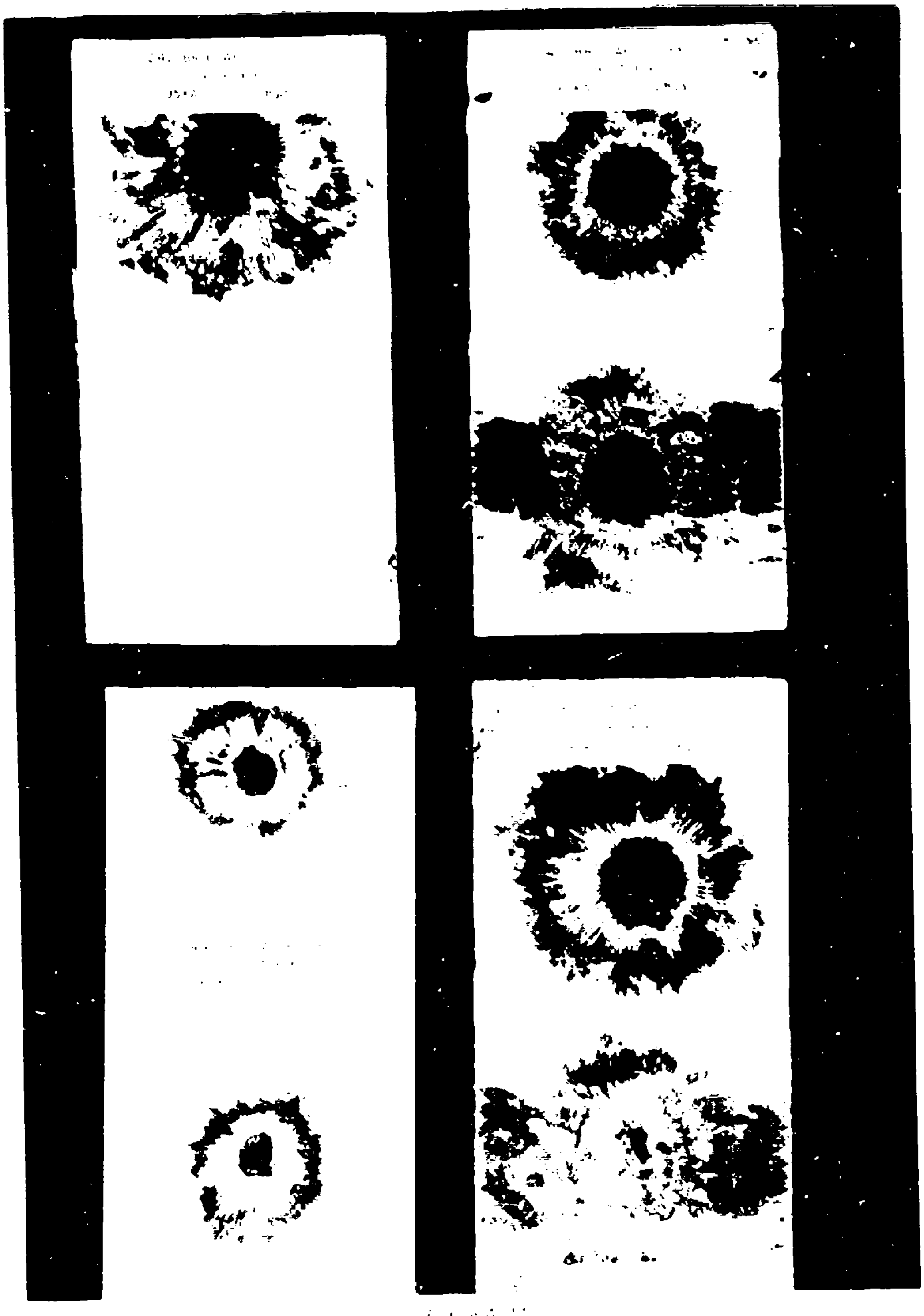
The whole panel was cracked at the center along the direction of the fiber; however, no visible damage to the substrate surface was observed.

042-BR16-AF01C-0000 Figure A-11 September 16, 1969

A 1-mil aluminum foil was integrally bonded to this boron panel on the scrim cloth side of the tape, and no undercoating was applied. An 18 KV discharge was directed to the coated panel; the discharge current had an amplitude of 95 KA with a risetime of 15 μs and a duration of 28 μs.

A crack was observed on the back side of the substrate.





043-BR17-AF01C-0000 Figure A-11 September 17, 1969
A 1-mil aluminum foil was integrally bonded to this boron panel on the boron side of the tape. No undercoating was applied. Two 18 KV discharges were directed to this coated panel, both of the discharges had a current crest of 95 KA with a risetime of 15 μs and a duration of 28 μs.

No visible damage to the substrate was observed. However, burned and vaporized aluminum foil was shown. The vaporized aluminum foil, as shown on the bottom of the panel, was caused by the second discharge located on the top of the panel.

044-GP10-AF06C-0000 Figure A-11 September 16, 1969
An epoxy adhesive, BMS 5-29, was used to bond a 6-mil aluminum foil to this graphite panel with no undercoating. Two 18 KV discharges were directed to this coated panel; both of the discharges had a current crest of 95 KA with a risetime of 15 μs and a duration of 28 μs.

No damage to the substrate was observed from the first discharge; however, a small burned substrate surface was produced at the second discharge.

045-BR18-AF01C-0000 Figure A-11 September 18, 1969
A 1-mil aluminum foil was integrally bonded to this boron panel on the boron side of the tape; no undercoating was applied. Two 18 KV discharges were directed to this coated panel; both of the discharges had a current crest of 95 KA with a risetime of 15 μs and a duration of 28 μs.

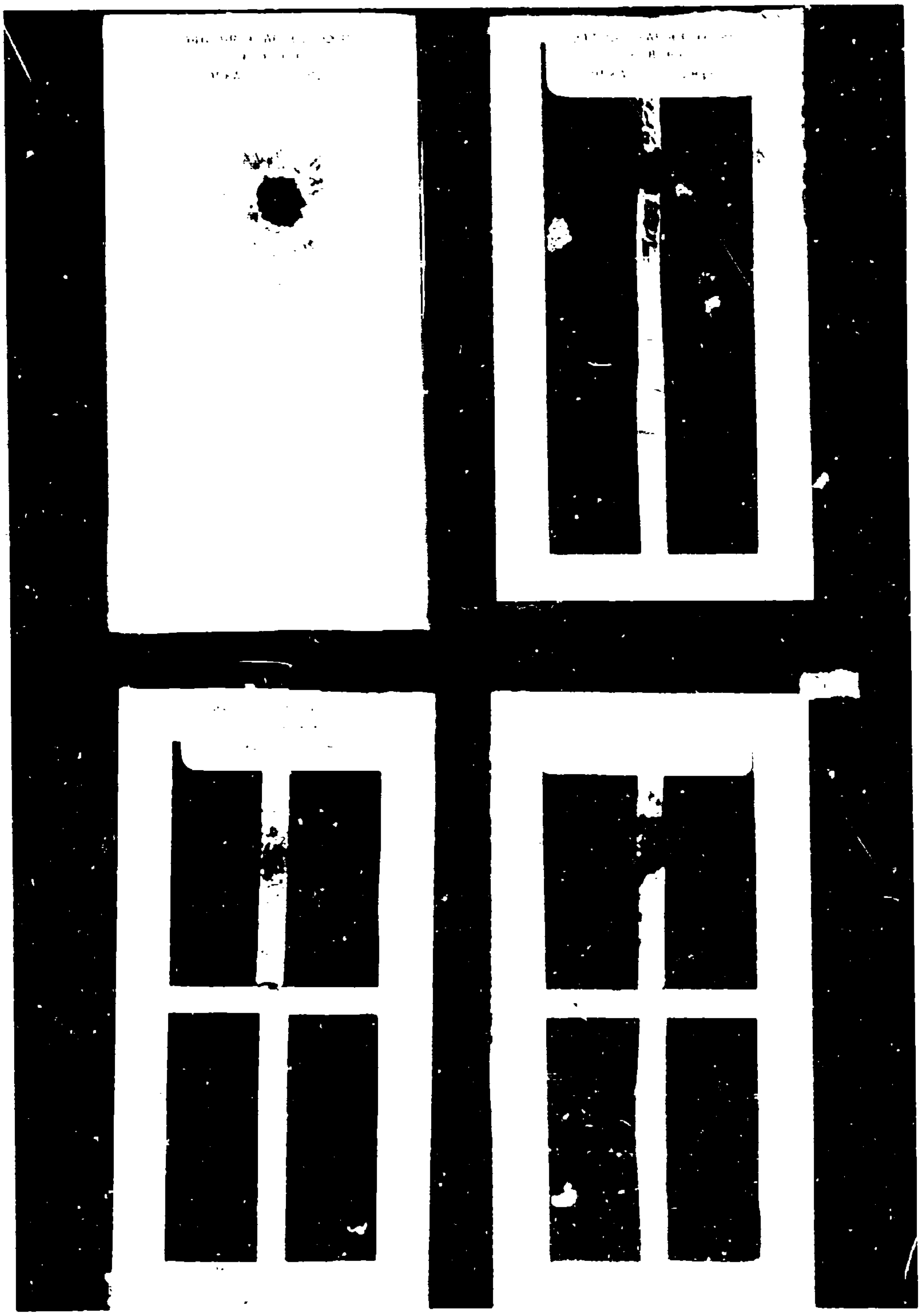
No visible damage to the substrate was observed except burned and vaporized aluminum foil; the vaporized aluminum as shown on the bottom of the panel was caused by the second discharge which was directed to the top of the panel.

046-BR19-AF06C-0000 Figure A-12 September 18, 1969
An epoxy adhesive, BMS 5-29, was used to bond a 6-mil aluminum foil to this boron panel with no undercoating. An 18 KV discharge was initiated to this coated panel; the discharge current had an amplitude of 95 KA with a risetime of 15 μs and a duration of 28 μs.

No damage to the substrate was observed.

047-GP11-AF06P-0000 Figure A-12 September 18, 1969
An epoxy adhesive, BMS 5-29, was used to bond 6-mil aluminum strips to this graphite panel with no undercoating. The top and center strips were a half inch wide; the strips on both sides and at the bottom were 1-inch wide. An 18 KV discharge was directed to the center strip; the discharge current had an amplitude of 95 KA with a risetime of 15 μs and a duration of 28 μs.

A burned front surface of the substrate was produced and a small crack was observed on the back side of the substrate.



<u>048-GP12-AF06P-0000</u> <u>Figure A-12</u> <u>September 18, 1969</u>
An epoxy adhesive, BMS 5-29, was used to bond 6-mil aluminum strips to this graphite panel with no undercoating. The center tapes were one-half inch wide and the side tapes were 1-inch wide. An 18 KV discharge was directed to this coated panel at the vertical center tape; the discharge was an underdamped oscillatory type due to the failure of the crowbar switching circuit. The discharge current had a peak amplitude of 95 KA with a ring frequency of 36 kHz.

A burned front surface of the substrate was observed, and a small crack on the back side of the substrate was found.

<u>049-BR20-AF06P-0000</u> <u>Figure A-12</u> <u>September 18, 1969</u>
An epoxy adhesive, BMS 5-29, was used to bond 6-mil aluminum strips to this boron panel with no undercoating. The center tapes were one-half inch wide and the side tapes were one inch wide. An 18 KV discharge was directed to this coated panel at the vertical center tape; the discharge current had an amplitude of 95 KA with a risetime of 16 μs and a duration of 28 μs.

No visible damage to the substrate was observed.

<u>050-BR21-AF06P-0000</u> <u>Figure A-13</u> <u>September 18, 1969</u>
An epoxy adhesive, BMS 5-29, was used to bond 6-mil aluminum strips to this boron panel; the center tape was one half inch wide and the side tapes were one inch wide. An 18 KV discharge was initiated to this coated panel; the discharge current had an amplitude of 95 KA with a risetime of 16 μs and a duration of 28 μs.

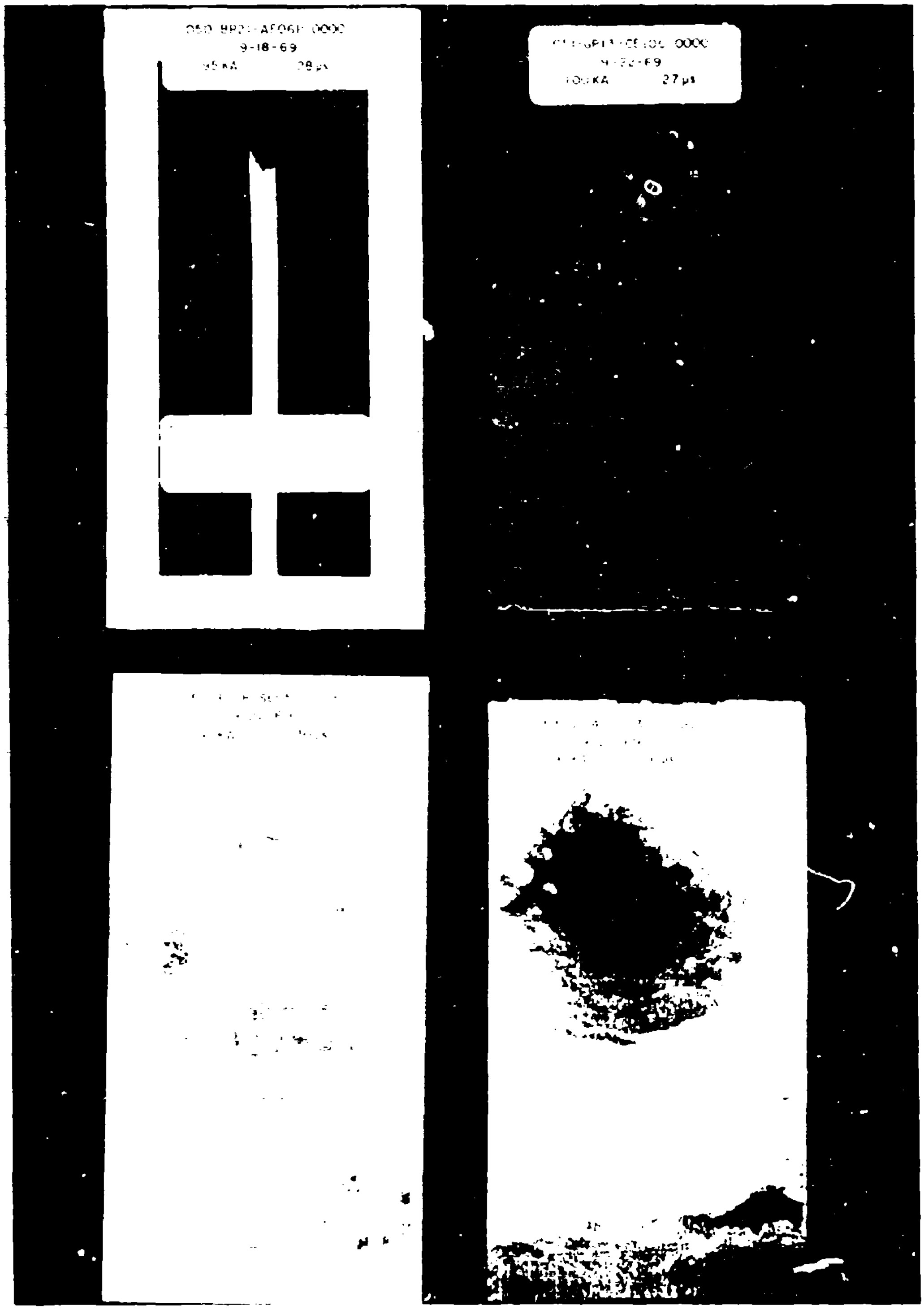
No visible damage to the substrate was observed.

<u>051-GP13-CE10C-0000</u> <u>Figure A-13</u> <u>September 22, 1969</u>
A copper filled epoxy paint was applied to this laminate. The coating thickness was very irregular, but averaged 10 mils. A 17 KV discharge was directed to this coated panel; the discharge current had an amplitude of 100 KA with a risetime of 15 μs and a duration of 27 μs.

A severely burned front surface of the substrate was observed and part of the paint was peeled.

<u>052-FG18-SE05C-0000</u> <u>Figure A-13</u> <u>September 22, 1969</u>
A silver filled epoxy paint (5 mils) was sprayed on this fiberglas panel with no undercoating. A 17 KV discharge was directed to this coated panel; the discharge current had a magnitude of 90 KA with a risetime of 15 μs and a duration of 30 μs.

No visible damage to the fiberglas panel was observed.


9-18-69
27 µs

053-GP14-SE03C-0000 Figure A-13 September 22, 1969

A silver filled epoxy paint (3 mils) was sprayed on this graphite panel with no undercoating. A 17 KV discharge was directed to this coated panel; the discharge current had a magnitude of 92 KA with a risetime of 13 μs and a duration of 26 μs.

A burned front surface of the substrate was observed and part of the coating was badly burned.

054-BR22-CU05C-0000 Figure A-14 September 22, 1969

A copper filled polyurethane paint (5 mils) was sprayed on this boron panel with no undercoating. A 17 KV discharge was directed to this coated panel; the discharge current had a magnitude of 36 KA with a risetime of 16 μs and a duration of 60 μs.

The substrate was severely damaged.

055-GP15-00000-0000 Figure A-14 September 22, 1969

This was an uncoated graphite panel. An 18 KV discharge was directed to this panel; the discharge current had a magnitude of 92 KA with a risetime of 14 μs and a duration of 28 μs.

The substrate was severely damaged.

056-GP16-00000-KF01 Figure A-14 September 23, 1969

This graphite panel had no coating; however, a 1-mil Kapton film was integrally bonded in the panel between the first and second plies. An 18 KV discharge was initiated to this panel; the discharge current had a magnitude of 89 KA with a risetime of 15 μs and a duration of 29 μs.

The substrate was damaged; however, compared to the uncoated graphite panel (055-GP15-00000-0000), this panel sustained lesser damage on the back side of the substrate.

057-FG19-AU05C-0000 Figure A-14 September 23, 1969

An aluminum filled polyurethane paint was sprayed on this fiberglas panel with no undercoating. A 17 KV discharge was directed to this coated panel; the discharge current had a magnitude of 90 KA with a duration of 30 μs.

No damage to the substrate was observed.

058-BR23-CE10C-0000 Figure A-15 September 23, 1969

A copper filled epoxy paint was applied to this laminate. The coating thickness was very irregular, but averaged 10 mils. An 18 KV discharge was directed to this coated panel; the discharge current had a magnitude of 67 KA with a risetime of 15 μs and a duration of 30 μs.

A small crack was observed on the back side of the substrate, also the coating was badly burned and peeled.

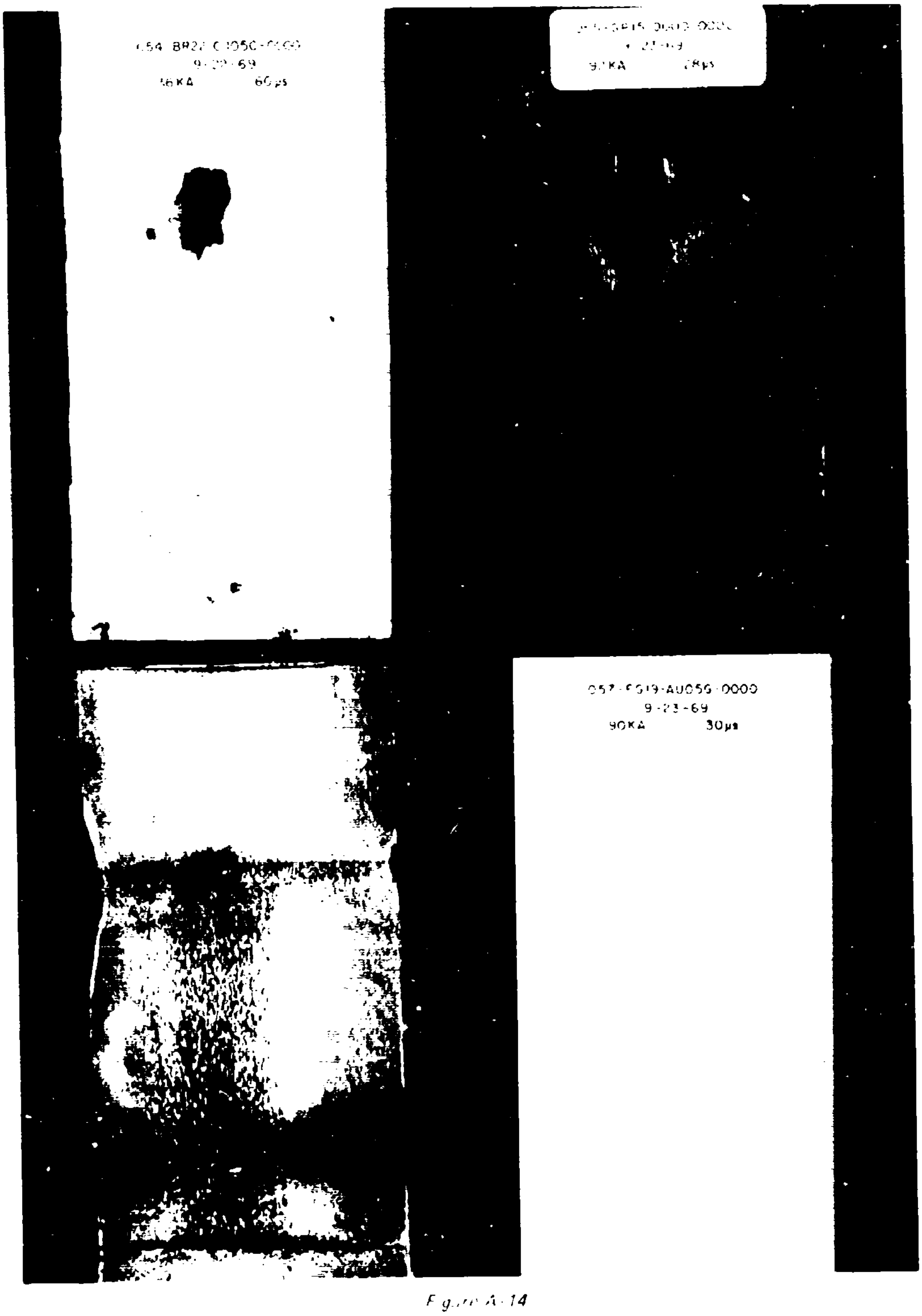
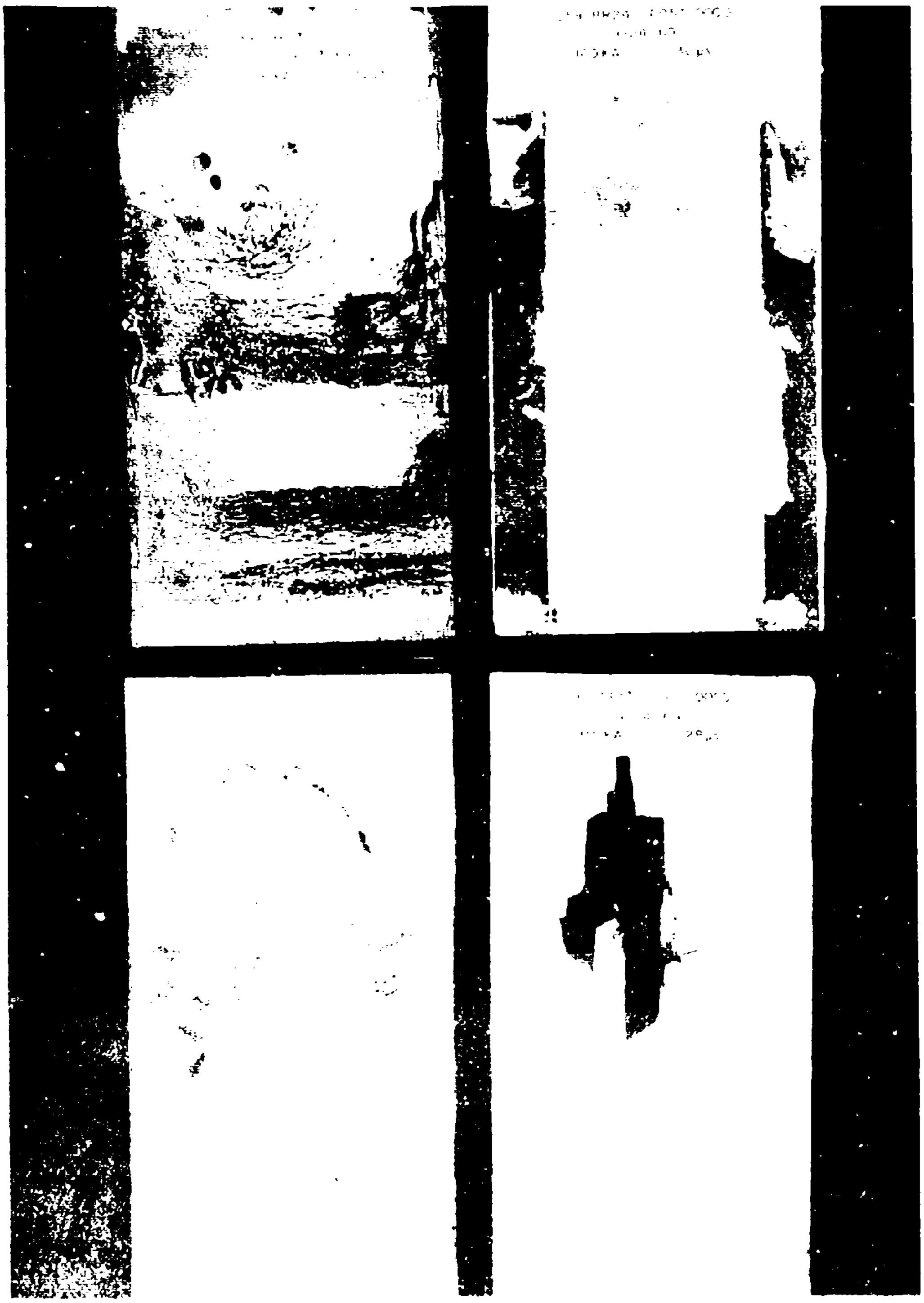


Figure A-14



059-BR24-SE05T-0000 Figure A-15 September 24, 1969
Aluminum tape was bonded to the edges of this panel. A silver filled epoxy paint was then sprayed over the panel. An 18 KV discharge was directed to this coated panel; the discharge current had a magnitude of 100 KA with a duration of 30 μs.

No damage to the substrate was observed. The aluminum tape was completely vaporized and part of the coating was burned.

060-BR25-SE05C-0000 Figure A-15 September 24, 1969
A silver filled epoxy paint (5 mils) was sprayed on this boron panel with no undercoating. An 18 KV discharge was directed to this coated panel; the discharge current had a magnitude of 90 KA with a duration of 30 μs.

A small crack on the back side of the substrate was observed and the silver-epoxy paint was badly burned.

061-GP17-CU05C-0000 Figure A-15 September 24, 1969
A copper filled polyurethane paint (5 mils) was sprayed on this graphite panel with no undercoating. A 23 KV discharge was directed to this coated panel, the discharge current had a magnitude of 110 KA with a risetime of 14 μs and a duration of 28 μs.

The substrate was severely damaged.

062-BR26-AU05C-0000 Figure A-16 September 24, 1969
A 5-mil aluminum filled polyurethane paint was sprayed on this boron panel with no undercoating. An 18 KV discharge was directed to this coated panel; the discharge current had a magnitude of 36 KA with a risetime of 20 μs and a duration of 60 μs.

The substrate was severely damaged.

063-GP18-AU05C-0000 Figure A-16 September 24, 1969
A 5-mil aluminum filled polyurethane paint was sprayed on this graphite panel with no undercoating. A 21 KV discharge was directed to this coated panel; the discharge current had a magnitude of 103 KA with a risetime of 15 μs and a duration of 28 μs.

The substrate was severely damaged.

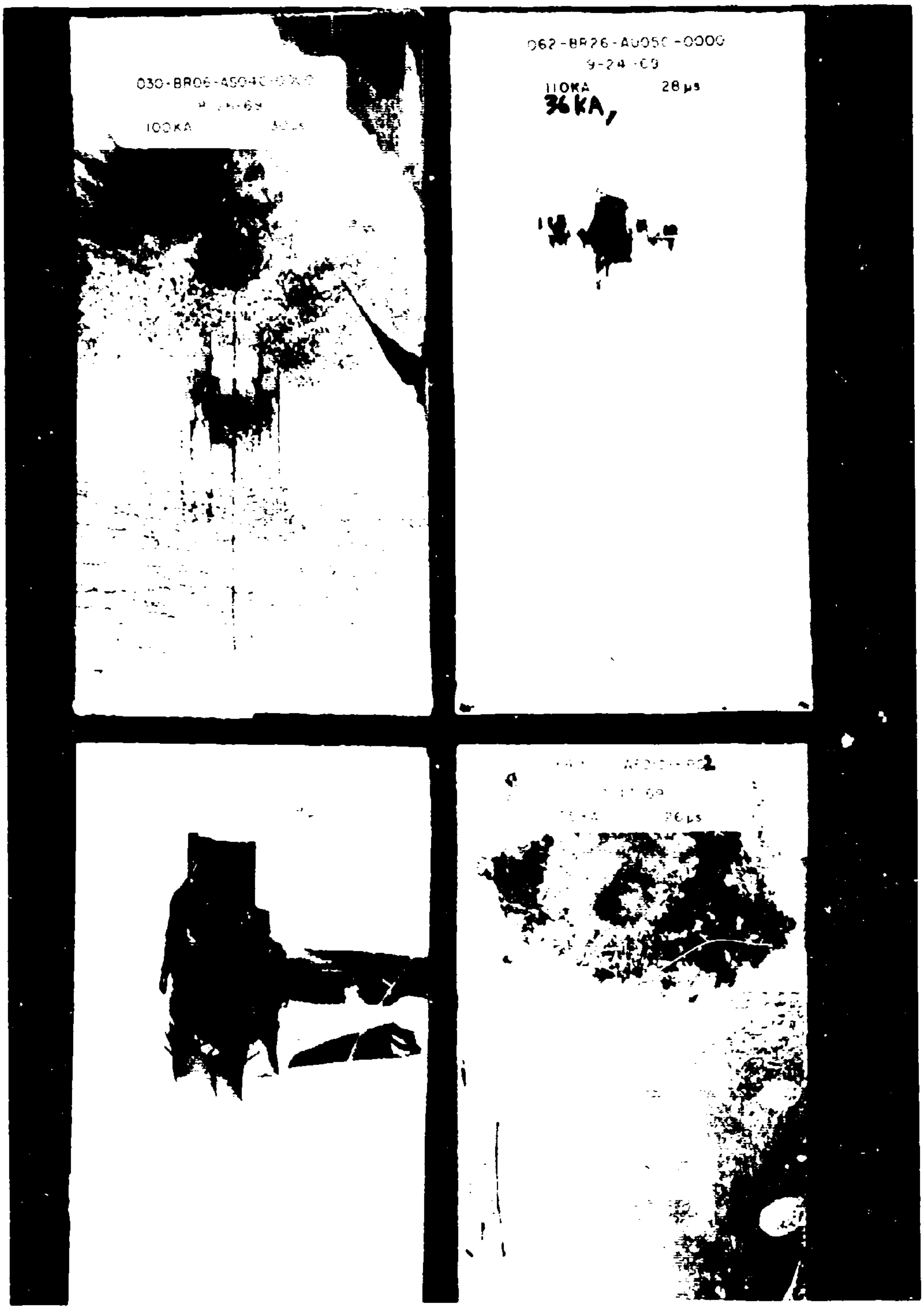


Figure A-16

064-FG20-AF01C-EP02 Figure A-16 October 17, 1969

This fiberglas panel was coated with 1-mil aluminum foil and an undercoating of 2-mil epoxy paint. An 18 KV discharge was initiated to this coated panel; it turned out to have a spike with an amplit de of 105 KA, a risetime of 14 μs, and a pulse duration of 27 μs.

No visible damage to the control panel was observed. However, the epoxy paint was burned; the left side of the aluminum foil along the 12" direction was peeled, curled, and burned. There were also other burned aluminum marks shown.

065-FG21-SE03C-CC07 Figure A-17 October 17, 1969

This fiberglas panel was coated with a 3-mil silver-epoxy paint with an undercoating of a 7.5-mil carbon cloth. However, the overall thickness of the composite coating was only about 8.5-mil due to absorption of the paint by the carbon cloth. An 18 KV discharge was initiated to this coated fiberglas panel; the discharge current had a peak of 70 KA with a risetime of 18 μs and a duration of 31 μs.

No damage to the control panel was observed; however, most of the silver paint was discolored.

066-FG22-CR09U-0000 Figure A-17 October 17, 1969

This fiberglas panel was coated with a 9-mil thick copper screen which was oriented so that its fibers lay in a direction 45° (or 135°) with respect to the 12-inch panel dimension. No undercoating was applied. An 18 KV discharge was initiated to this coated fiberglas panel; the current peak was of 98 KA with a risetime of 14 μs and a duration of 27 μs.

No damage to the control panel was observed and the copper screen along the left side was peeled off.

067-FG23-CR09U-0000 Figure A-17 October 17, 1969

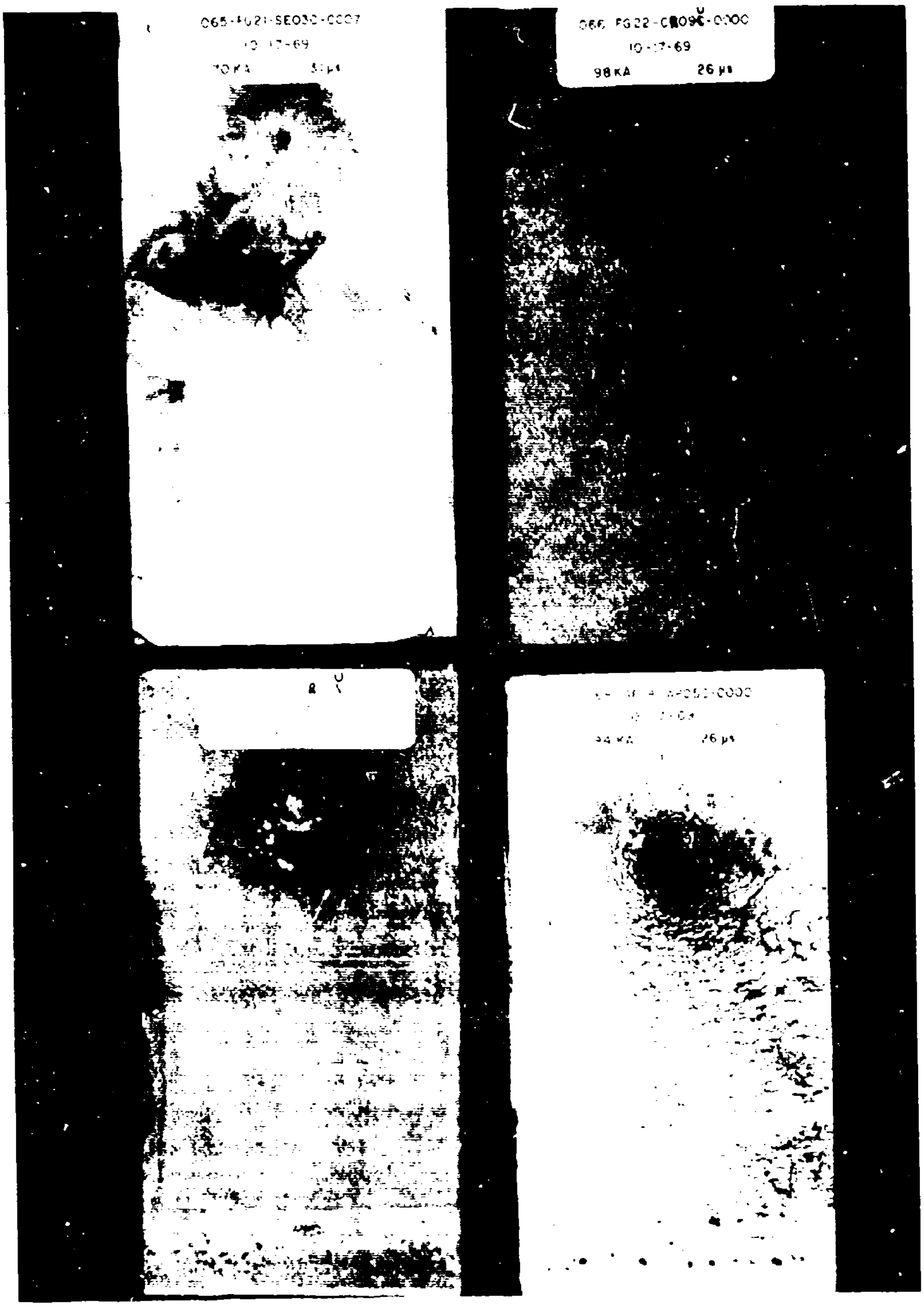
This fiberglas panel was coated with a 9-mil thick copper fabric which was oriented 90° (or 0°) with respect to the direction of discharge current flow. No undercoating was applied. An 18 KV discharge was initiated to this coated fiberglas panel; the current was of 98 KA with a risetime of 14 μs and a duration of 27 μs.

No damage to the fiberglas panel was observed and copper fabric along both edges was peeled off.

068-GP19-AP05C-0000 Figure A-17 October 17, 1969

This graphite panel was coated with a 5-mil plasma-sprayed aluminum coating with no undercoating. An 18 KV discharge was initiated to this coated fiberglas panel; the discharge current was of 94 KA with a risetime of 15 μs and a duration of 26 μs.

The front two layers of substrate were burned; the aluminum paint was badly cracked and part of the paint was discolored.



10-17-69
98 KA
26 μs

069-FG24-AF04P-AU06 Figure A-18 October 17, 1969

This fiberglas panel was first coated with aluminum filled polyurethane paint, then two aluminum strips were taped to the panel along both of the 12-inch edges. The crowbar switch was disconnected from the simulator. A 20 KV discharge was initiated to this coated fiberglas panel; the peak of the discharge current was of 91 KA with a risetime of 13 μs and a duration of 27 μs.

No damage to the panel was observed although the aluminum strips were vaporized.

070-FG25-AU06C-CC07 Figure A-18 October 20, 1969

This fiberglas panel is coated with aluminum filled polyurethane paint with an undercoating of a 7-mil thick carbon cloth. The overall thickness of the composite coating was about 10 mil due to absorption of paint by the carbon cloth. The crowbar switch was disconnected from the simulator. A 20 KV discharge was initiated to this coated fiberglas panel; the discharge current was 95 KA with a risetime of 14 μs and a duration of 27 μs.

No damage to the control panel was observed.

071-FG26-AF04P-CC07 Figure A-18 October 20, 1969

This fiberglas panel was coated with a 7.5-mil carbon cloth, then 4-mil thick aluminum foil tape was applied along the edges of the 12-inch side. The crowbar switch was disconnected from the simulator. A 20 KV discharge was initiated to this coated panel; the discharge current had a peak of 105 KA with a risetime of 14 μs and a duration of 27 μs.

No damage to the control panel was observed although the aluminum tapes were vaporized.

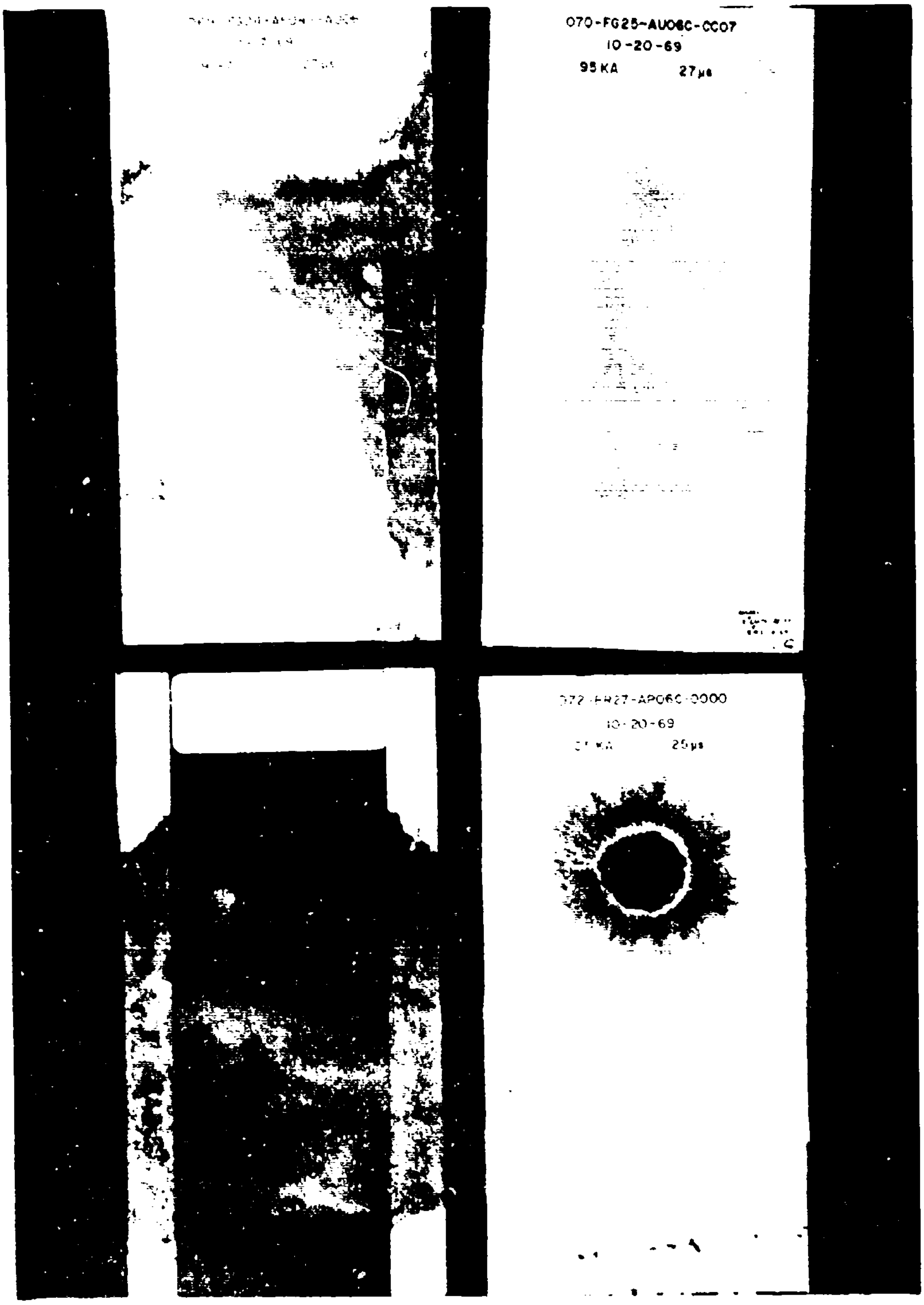
072-BR27-AP06C-0C00 Figure A-18 October 20, 1969

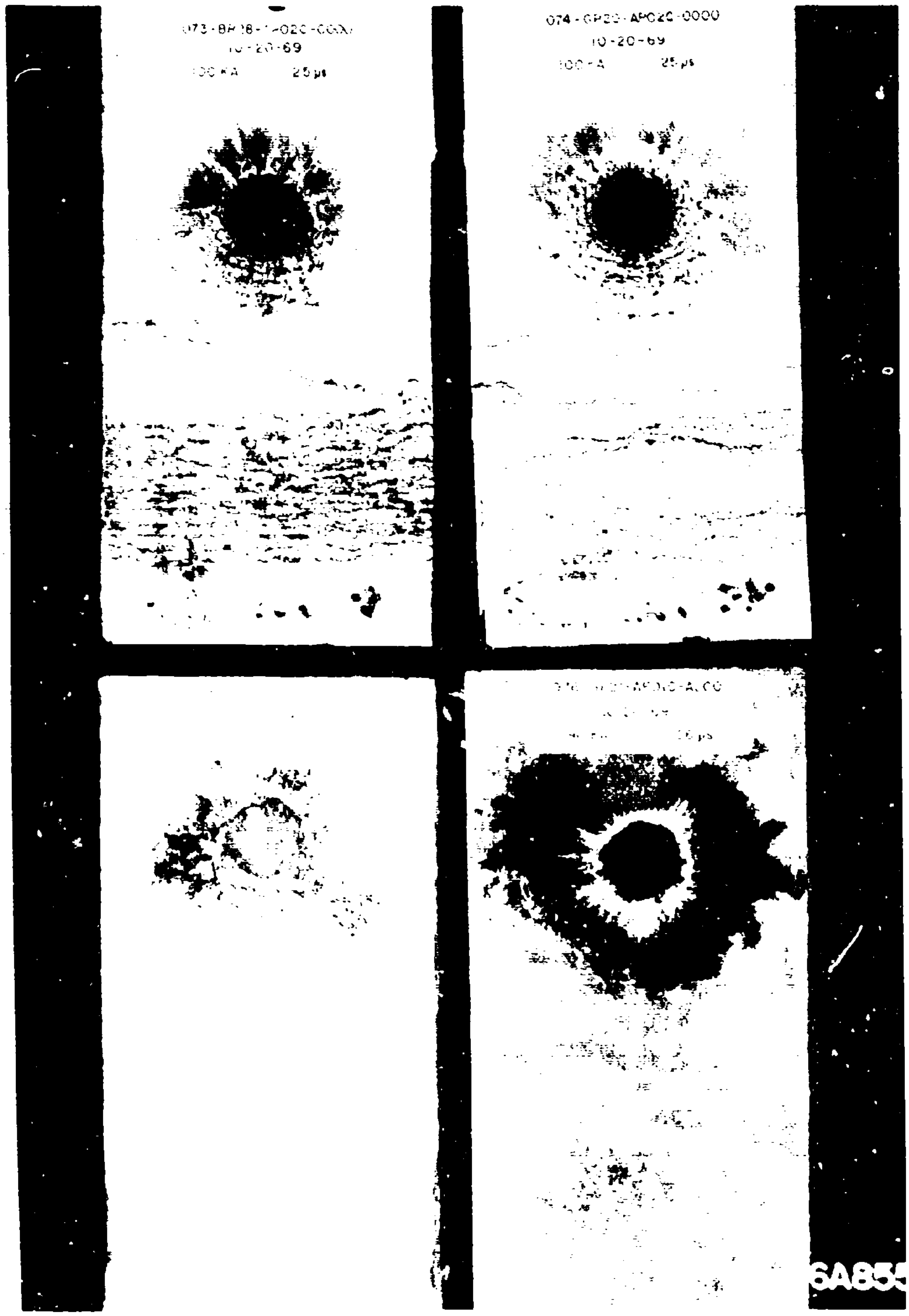
This boron panel was coated with a 6-mil plasma-sprayed aluminum paint with no undercoating. An 18 KV discharge was initiated to this coated panel; the discharge current had a peak of 105 KA, a risetime of 13 μs and a duration of 25 μs.

The appearance of this tested panel is similar to the panels coated with an aluminum foil. The back side of the substrate showed a barely visible crack immediately under the discharge probe. The setup of this test was exactly the same as the one for the tested panel 068, which also passed the tests without damage to the substrate.

073-BR28-AP02C-0000 Figure A-19 October 20, 1969

This boron panel was coated with a 2-mil plasma-sprayed aluminum paint with no undercoating. An 18 KV discharge was initiated to this coated panel; the discharge current had a peak of 100 KA with a risetime of 13 μs and a duration of 25 μs.


070-FG25-AU06C-CC07
10-20-69
95 KA 27 μs
10-20-69
25 μs


10-20-69
25 µs
10-20-69
25 µs
6A855

A very small crack was observed on the back side of the substrate; the front surface paint was badly burned.

074-GP20-AP02C-0000 Figure A-19 October 20, 1969
This graphite panel was coated with a 2-mil plasma-sprayed aluminum paint with no undercoating. An 18 KV discharge was initiated to this coated panel; the discharge current had a peak of 100 KA with a risetime of 13 μs and a duration of 25 μs.

No damage to the substrate was observed, however, the front surface paint was badly burned.

075-BR29-AF01C-ALCO Figure A-19 October 21, 1969
This boron panel was coated with 1-mil aluminum foil and was then bonded to an aluminum honeycomb core. When this panel was mounted to the test holder, both the aluminum foil and honeycomb core were grounded. A 16 KV discharge was initiated to this test panel; the discharge current had a peak of 90 KA with a risetime of 14 μs and a duration of 26 μs.

076-GP21-AF01C-ALCO Figure A-19 October 21, 1969
This graphite panel was coated with a 1-mil aluminum foil and was then bonded to an aluminum honeycomb core. Both the aluminum foil and honeycomb core were grounded when the test panel was mounted on the test holder. A 16 KV discharge was initiated to this test panel. The current waveform was not recorded, however, since the test setup was exactly the same as the last one, presumably, the current was also the same, i.e., the peak was 90 KA with a risetime of 14 μs and a duration of 26 μs.

077-BR30-CR09U-0000 Figure A-20 October 21, 1969
This boron panel was coated with a 9-mil copper fabric which was oriented 45° (or 135°) with respect to the direction of the current flow. No undercoating was applied. A 16 KV discharge was initiated to this coated panel; the discharge current had a peak of 90 KA with a risetime of 13 μs and a duration of 25 μs.

No damage to the substrate was observed.

078-GP22-CR09U-000 Figure A-20 October 21, 1969
This graphite panel was coated with a 9-mil copper fabric which was oriented 45° in relation to the direction of the discharge current flow. A 16 KV discharge was initiated to this coated panel; the discharge current had a peak of 90 KA with a risetime of 13 μs and a duration of 27 μs.

No damage to the substrate was observed.

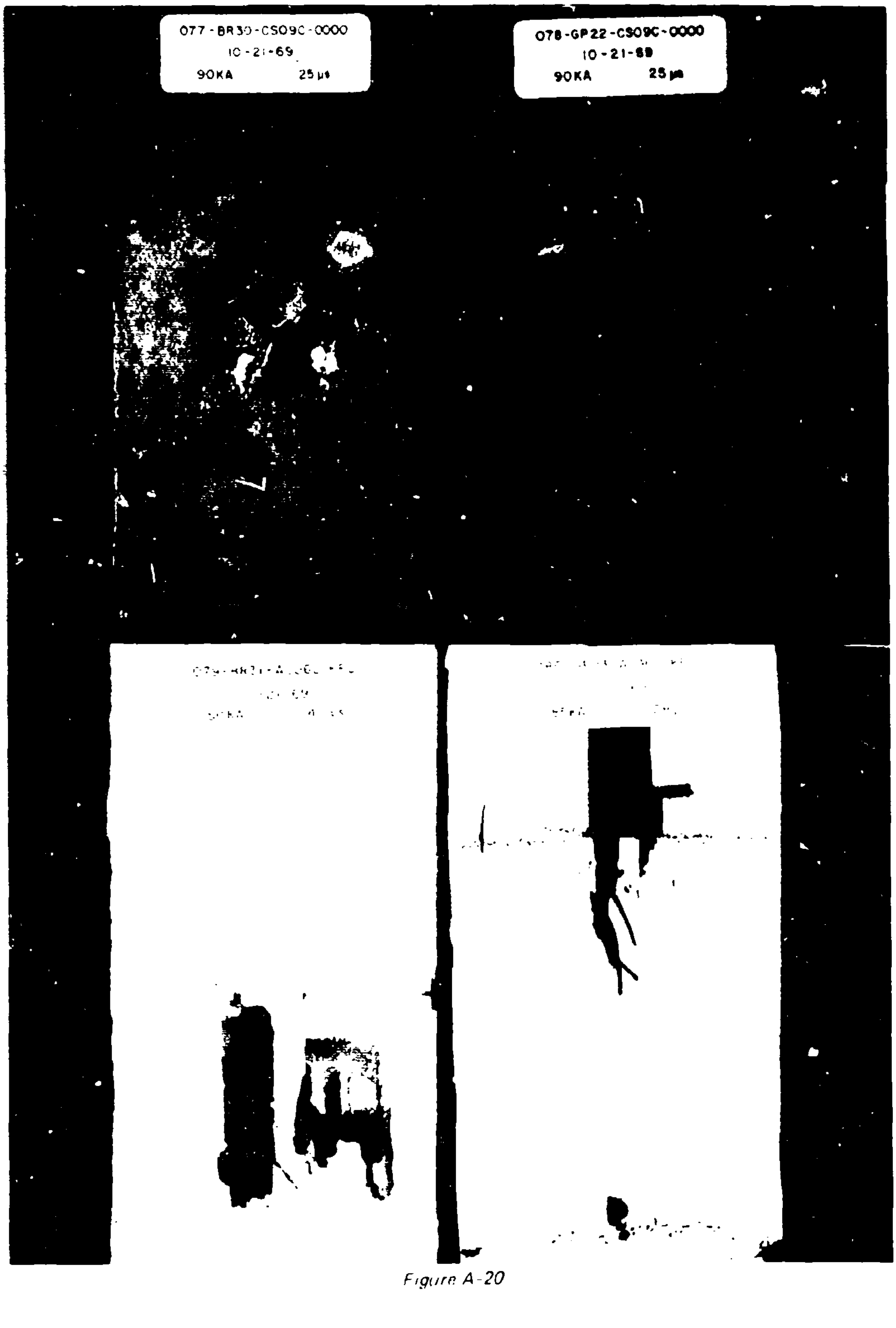

077-BR30-CS09C-0000
10-21-69
90KA 25 μs
078-GP22-CS09C-0000
10-21-69
90KA 25 μs

Figure A-20

079-BR31-AU06C-KF01 Figure A-20 October 21, 1969

This boron panel was coated with 6-mil aluminum filled polyurethane paint and was undercoated with a one mil Kapton film interlayer between the 4th and 5th layers. A 20 KV discharge was initiated to the coated panel; the discharge current had a peak of 50 KV with a risetime of 18 μs and a duration of 40 μs.

The substrate was severely damaged.

080-GP23-AU06C-KF01 Figure A-20 October 21, 1969

This graphite panel was coated with aluminum filled polyurethane paint with an interlayer undercoating of a one mil Kapton film which was between the 4th and 5th layers. A 20 KV discharge was initiated to this coated panel; the discharge current had a peak of 85 KA with a risetime of 14 μs and a duration of 28 μs.

The substrate was severely damaged.

081-BR32-CR09U-0000 Figure A-21 October 21, 1969

This boron panel was coated with an overall 9-mil thick copper fabric whose fibers were oriented in line, and perpendicular to the discharge current flow. A 17 KV discharge was initiated to this test panel; the discharge current had an amplitude of 90 KA with a risetime of 14 μs and a duration of 26 μs.

No damage to the substrate was observed.

082-GP24-CR09U-0000 Figure A-21 October 21, 1969

This graphite panel was coated with a 9-mil thick copper fabric whose fibers were oriented in line, and perpendicular to the discharge current flow. A 17 KV discharge was initiated to this test panel; the discharge current had a peak of 90 KA with a risetime of 14 μs and a duration of 26 μs.

No damage to the substrate was observed.

083-GP25-AU06C-CC07 Figure A-21 October 22, 1969

This graphite panel was first coated with a 7-mil carbon cloth and was then coated with 6 mil polyurethane paint pigmented with aluminum particles; however, the overall thickness of the composite coating was thinner than 10 mil due to absorption of the paint by the carbon cloth. A 20 KV discharge was initiated to this test panel; the crowbar switch was disconnected from the simulator. The discharge current had a peak of 70 KA with a risetime of 14 μs and a duration of 28 μs.

The test panel was severely damaged.

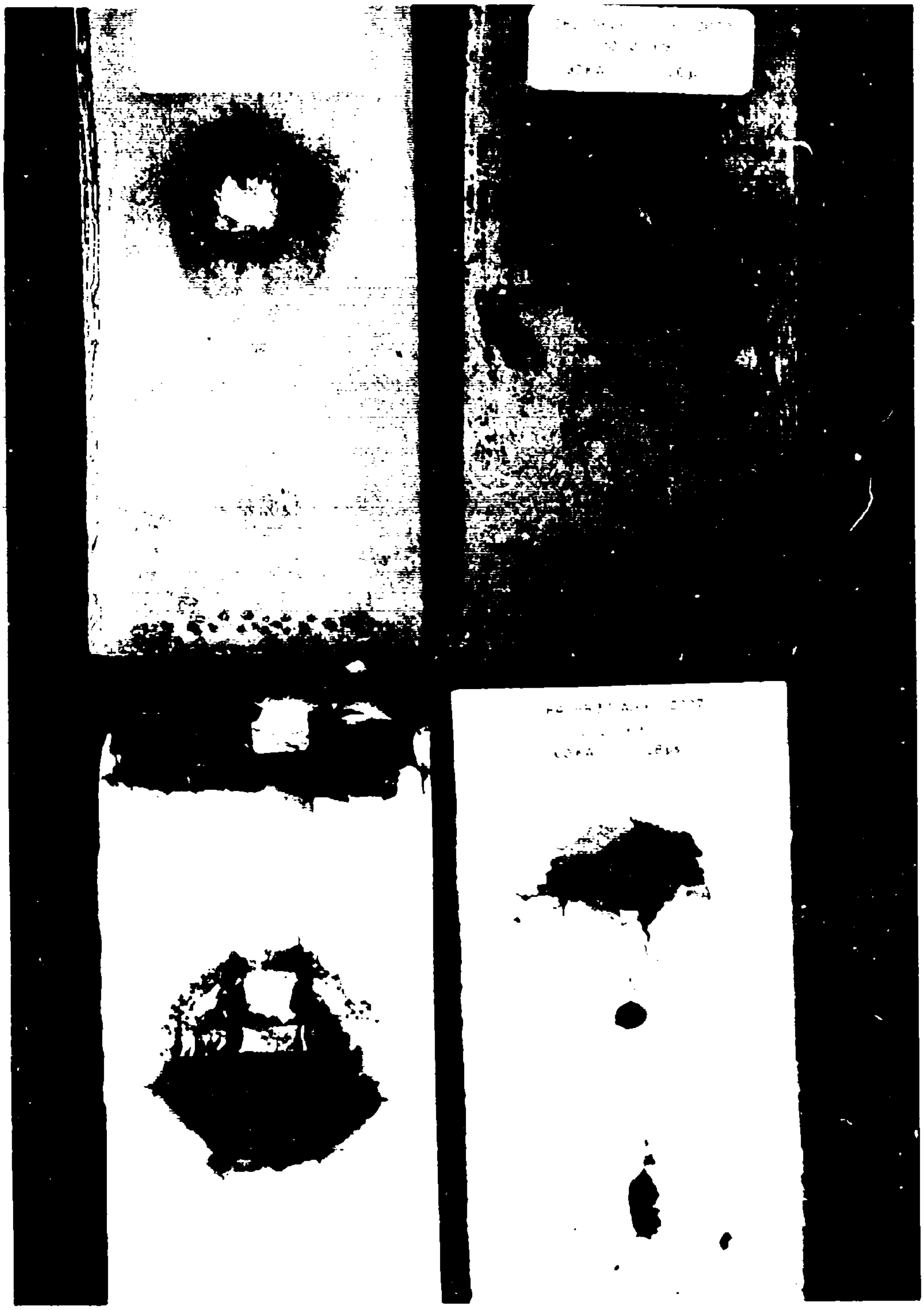


Figure A-21

084-BR33-AU06C-CC07 Figure A-21 October 22, 1969

This boron panel was first coated with a 7-mil carbon cloth and was then coated with 6-mil polyurethane paint pigmented with aluminum particles; however, the overall thickness of the composite coating was thinner than 10 mil due to absorption of the paint by the carbon cloth. A 20 KV discharge was initiated to this test panel with the crowbar switch disconnected from the simulator. The discharge current had a peak of 60 KA with a risetime of 14 μs and a duration of 28 μs.

This test panel was severely damaged.

085-BR34-AF04P-AU06 Figure A-22 October 22, 1969

This boron panel was first coated with an aluminum filled polyurethane paint and then coated with two 4-mil aluminum strips that were taped to the panel edge along the 12-inch side. The crowbar switch was disconnected from the simulator discharge path. A 20 KV discharge was initiated to this test panel; the discharge current had a peak of 90 KV with a ringing frequency of 36 KHz.

This panel was severely damaged.

086-GP26-AF04P-AU06 Figure A-22 October 22, 1969

This graphite panel was first coated with an aluminum filled polyurethane paint and two 4-mil aluminum strips were then taped to the panel along both 12-inch edges. An 18 KV discharge was initiated to this test panel; the discharge current had a peak of 90 KA with a risetime of 13 μs and a duration of 25 μs.

The panel was severely damaged.

087-BR35-AF04P-CC07 Figure A-22 October 22, 1969

This boron panel was first coated with a 7-mil carbon cloth and two 4-mil aluminum strips were then taped to the coated panel along both edges of 12-inch side of the panel. An 18 KV discharge was initiated to this coated panel; the discharge current had a peak of 88 KA with a risetime of 14 μs and a duration of 27 μs.

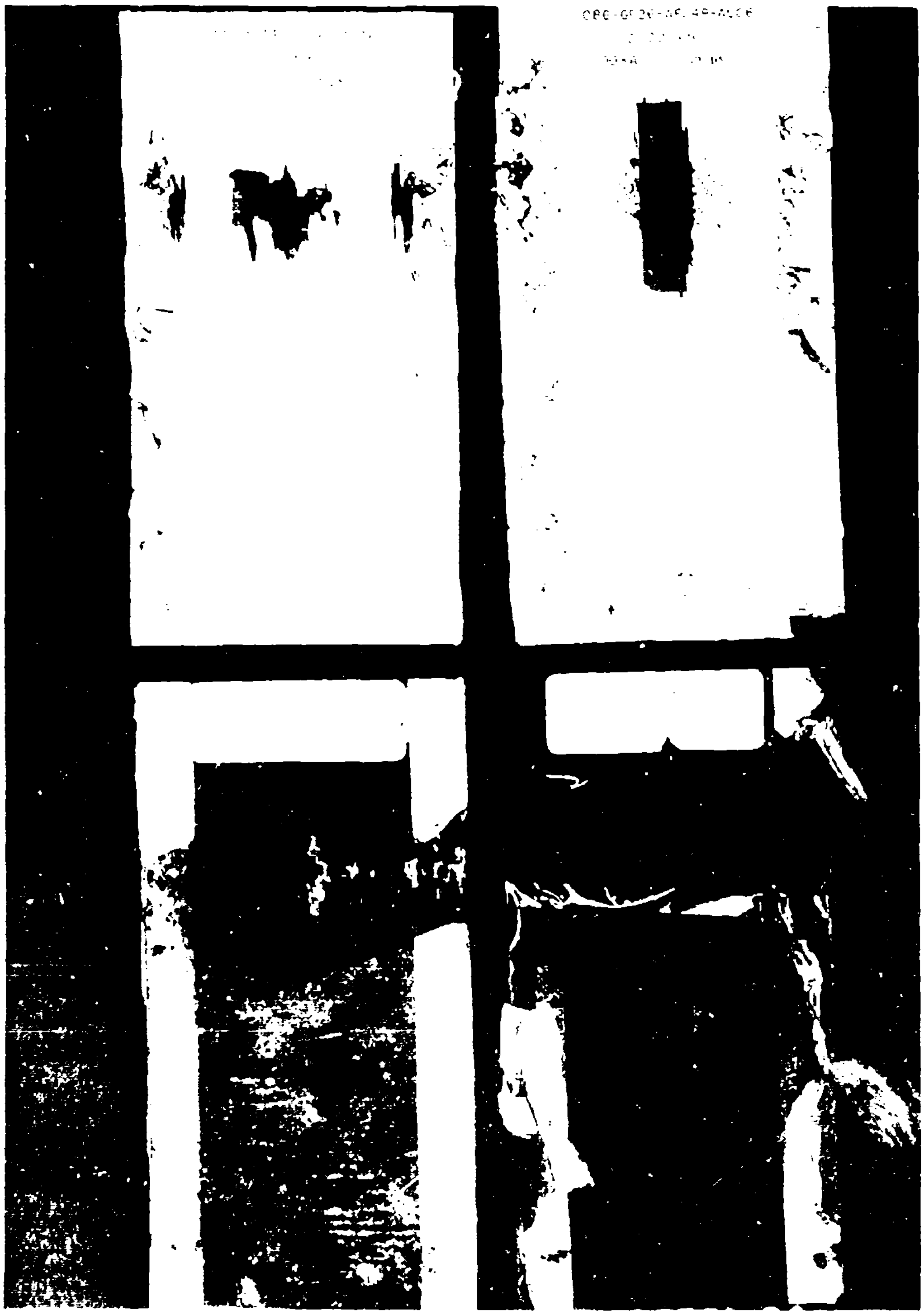
The panel was severely damaged.

The discharged stroke was crowbarred, or switched, earlier in time than desired. It was discovered later that this early crowbarring was caused by an enlarged gap between the probe and the test panel.

088-GP27-AF04P-CC07 Figure A-22 October 22, 1969

This graphite panel was first coated with a 7-mil carbon cloth and then two 4-mil aluminum strips were taped to this coated graphite panel along both edges of the 12-inch side. An 18 KV discharge was initiated to the panel; the discharge current had a peak of 90 KA with a risetime of 14 μs and a duration of 28 μs.

The panel was severely damaged.



The discharge was crowbarred at an early time, and it was found that this early crowbar was caused by an enlarged gap between the probe and the test panel. The gap was adjusted to a smaller distance (≈ 3/16") for the following tests.

<u>089-BR36-SE03C-CC05 Figure A-23 October 23, 1969</u>
This boron panel was first coated with a 5-mil carbon cloth and then was coated with a 3-mil silver filled epoxy paint, however, the overall thickness of this composite coating was only about 6.5-mil due to absorption of paint by the carbon cloth. An 18 KV discharge was initiated to this coated panel; the discharge current had a peak of 81 KA with a risetime of 14 μs and a duration of 27 μs.

A hole was punctured through the substrate, carbon cloth was peeled off, and all of the surface paint was discolored.

<u>090-GP28-SE03C-CC07 Figure A-23 October 23, 1969</u>
This graphite panel was first coated with a 7-mil carbon cloth and then was coated with a 3-mil silver filled epoxy paint, however, the overall thickness of this composite coating was only about 8.5-mil due to absorption of paint by the carbon cloth. An 18 KV discharge was initiated to this coated panel; the discharge current had a peak of 81 KA with a risetime of 14 μs and a duration of 27 μs.

The panel was severely damaged.

<u>091-BR37-SE03C-0000 Figure A-23 October 23, 1969</u>
This boron panel was coated with a 3-mil silver filled epoxy paint with no undercoating. An 18 KV discharge was initiated to this coated panel; the discharge current had a peak of 85 KA with a risetime of 15 μs and a duration of 29 μs.

A few small holes were punctured through the substrate and the surface paint was discolored.

<u>092-BR38-SE03C-CC07 Figure A-23 October 23, 1969</u>
This boron panel was first coated with a 7-mil carbon cloth and then was coated with a 3-mil silver filled epoxy paint; the overall thickness of this composite coating was only about 8.5-mil due to absorption of paint by the carbon cloth. An 18 KV discharge was initiated to this test panel; the discharge current had a peak of 85 KA and a risetime of 15 μs and a duration of 28 μs.

The substrate was damaged and the surface paint was discolored.

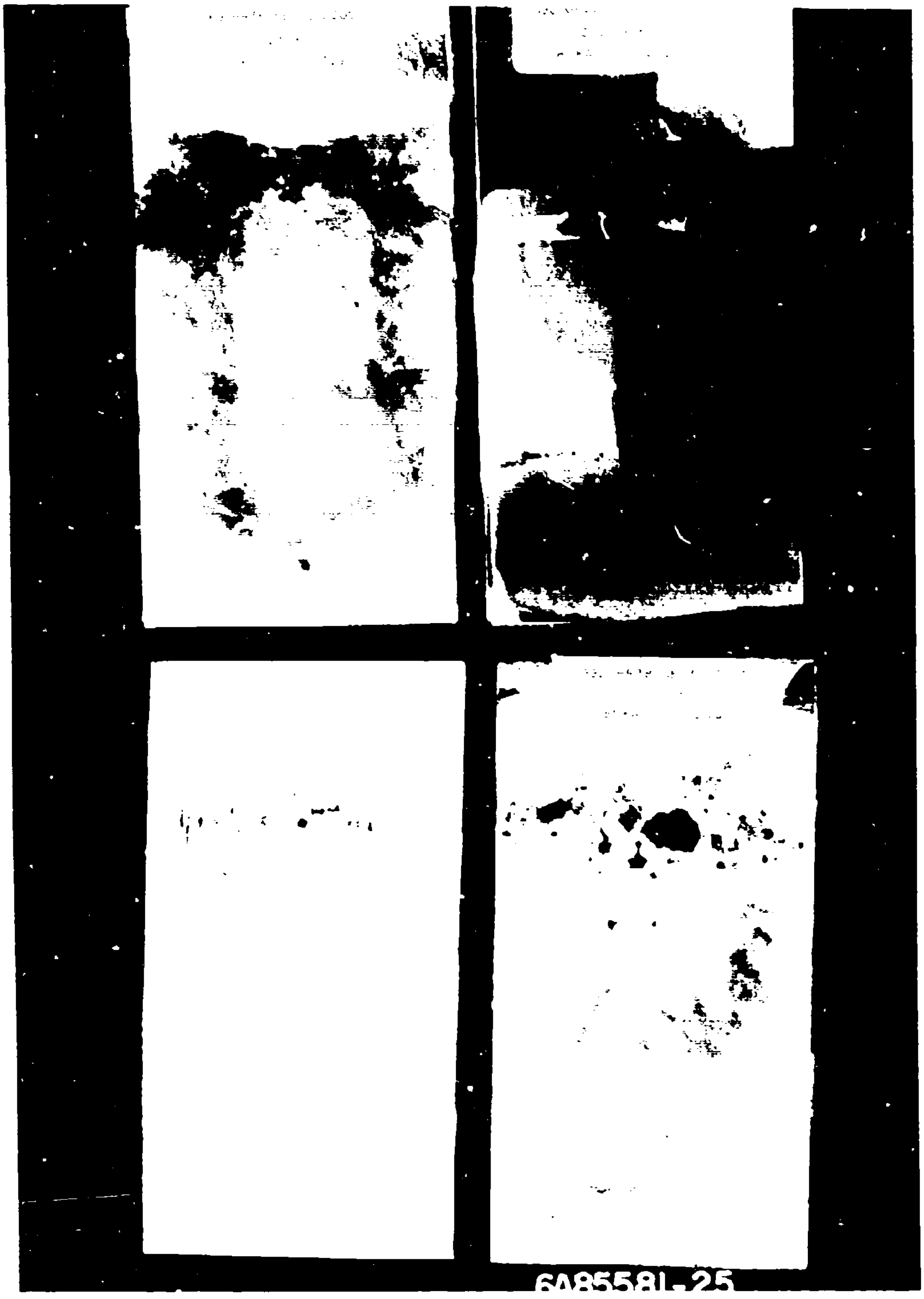


Figure A 23

093-GP29-AK05C-0000 Figure A-24 October 23, 1969

This graphite panel was coated with a 5-mil aluminum filled silicone paint with no undercoating. The crowbar switch was disconnected from the simulator. A 20 KV discharge was initiated to the coated panel; the discharge current had a peak of 90 KA with a risetime of 13 μs and a duration of 29 μs.

The substrate was severely damaged.

094-BR39-AK05C-0000 Figure A-24 October 23, 1969

This boron panel was coated with a 5-mil aluminum filled silicone paint with no undercoating. The crowbar switch was disconnected from the simulator. A 23 KV discharge was initiated to this coated panel; the discharge current had a peak of 51 KA and was critically damped. The stroke had a risetime of 22 μs and a duration of 70 μs.

The substrate was severely damaged.

095-FG27-AF03C-CC05 Figure A-24 November 19, 1969

This fiberglas panel was first coated with a 5-mil carbon cloth and was then coated with a 3-mil aluminum foil; both of these coatings were adhesively bonded to the panel and to each other by BMS 5-29 adhesive. A 16 KV discharge was directed to this coated panel. The discharge current was approximately 100 KA with a duration of 26 μs and a risetime of 14 μs.

No visible damage to the fiberglas panel was observed; however, the carbon cloth undercoating was slightly burned.

096-BR40-CW02P-0000 Figure A-24 November 19, 1969

This boron panel was partially coated with thin copper wires; no undercoating was applied. The thin copper wires of two mil diameter were adhesively bonded to the panel and each wire was either vertically or horizontally parallel to the edge of the panel. The wires parallel to the edge of the 12-inch dimension of the panel were 1/2 inch apart and the wires parallel to the 6-inch dimension were 2 inches apart.

The crowbar switch was disconnected from the simulator discharge path. A 23 KV discharge was initiated to this coated panel; the discharge current had a peak of 114 KA with a ring frequency of 24 kHz. The substrate was badly broken, and the thin copper wires were vaporized.

097-FG28-CK07C-0000 Figure A-24 November 19, 1969

A 7-mil silicone paint filled with copper powder was applied to the panel by spraying; no undercoating was applied.

The crowbar switch was disconnected from the simulator. A 20 KV discharge was directed to this coated panel; the discharge current had a peak of 114 KA with a ring frequency of 24 kHz.

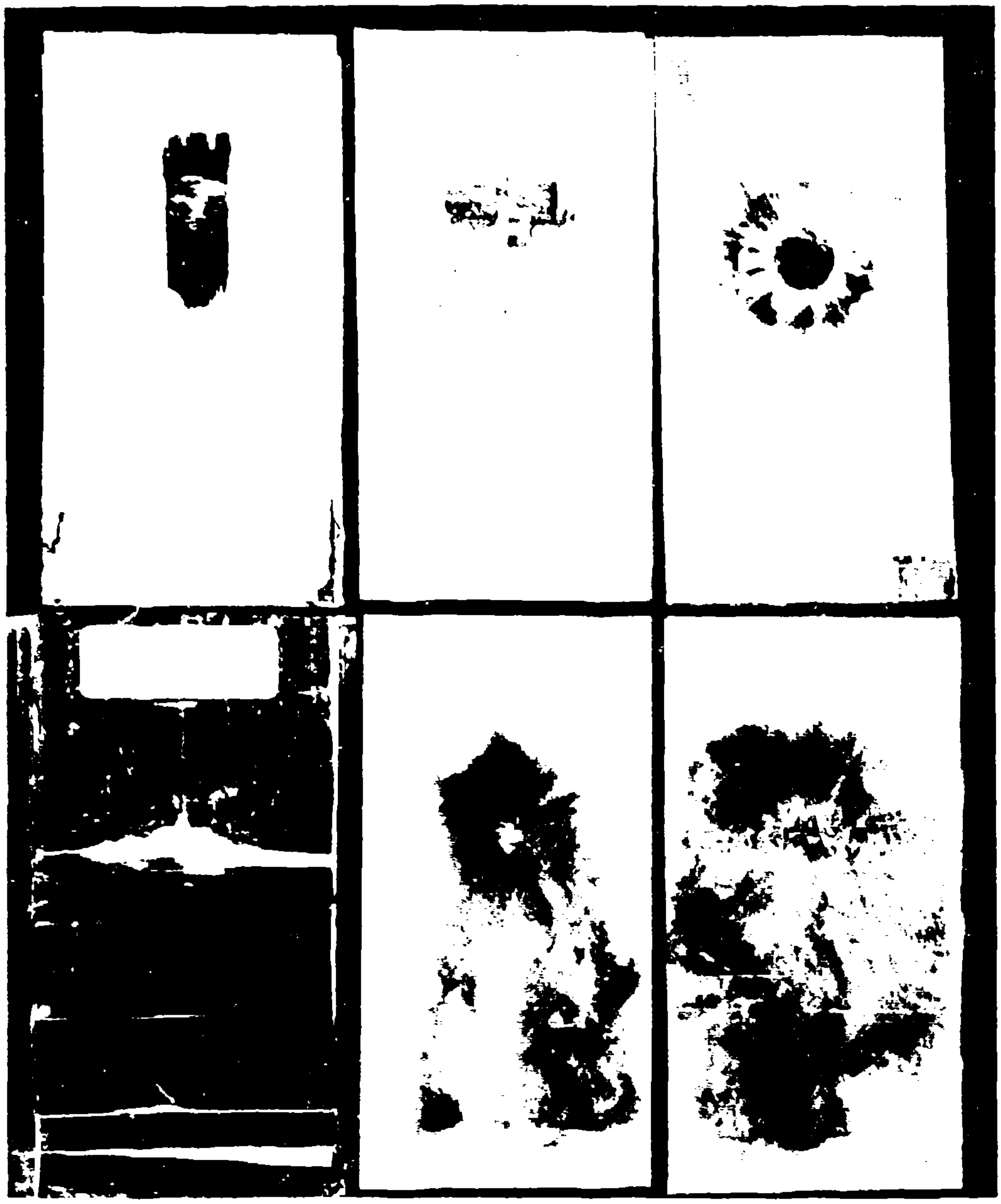


Figure A-24

No damage to the control panel was observed; however, the coating was discolored and partially burned. Surface flashover was also produced.

098-BR41-CK07C-0000 Figure A-24 November 19, 1969
A 7-mil silicone paint filled with copper powder was applied to the panel by spraying; no undercoating was applied. The crowbar switch was disconnected from the simulator. A 20 KV discharge was initiated to this coated panel; the discharge current had a peak of 100 KA with a ring frequency of 24 kHz.

The substrate was broken along the direction of the 6-inch dimension, and the coating was burned and discolored.

099-BR42-CF02C-0000 Figure A-25 November 20, 1969
A 2-mil thick copper foil was adhesively bonded to this boron panel with no undercoating. A 16 KV discharge was directed to this panel. The crowbar switch failed to turn on due to a mistriggered pulse generator. The discharge current had a peak of 95 KA with a ring frequency of 24.5 kHz.

No damage to the substrate was observed; the edges of the foil along the 12-inch side were curled.

100-GP30-CW02P-0000 Figure A-25 November 20, 1969
This graphite panel was partially coated with thin copper wires; no undercoating was applied. The thin copper wires of 2-mil diameter were adhesively bonded to the panel and each wire was either vertically or horizontally parallel to the edge of the panel. The wires parallel to the edge of the 12-inch dimension of the panel were 1/2 inch apart and the wires parallel to the 6-inch dimension were 2 inches apart. A 16 KV discharge was directed to this coated panel, the discharge current had a peak of 72 KA with a duration 30 μs and a risetime of 15 μs.

The substrate was broken.

101-GP31-CF02C-0000 Figure A-25 November 20, 1969
A 2-mil copper foil was adhesively bonded to this graphite panel with no undercoating. A 16 KV discharge was directed to this coated panel; the discharge current had a peak of 91 KA with a duration of 27 μs and a risetime of 14 μs.

The substrate surface was burned, and the backside was slightly cracked.

102-GP32-AF03P-SE02 Figure A-25 November 20, 1969
This graphite panel was first coated with a 2-mil silver filled epoxy paint and then two 3-mil thick, 1-inch wide, aluminum strips were bonded along the edges of the 12-inch side of the panel. A 16 KV discharge was directed to this coated panel; the discharge current had a peak of 91 KA with a duration of 27 μs and a risetime of 14 μs.

The substrate surface was burned, and the back side was slightly cracked.

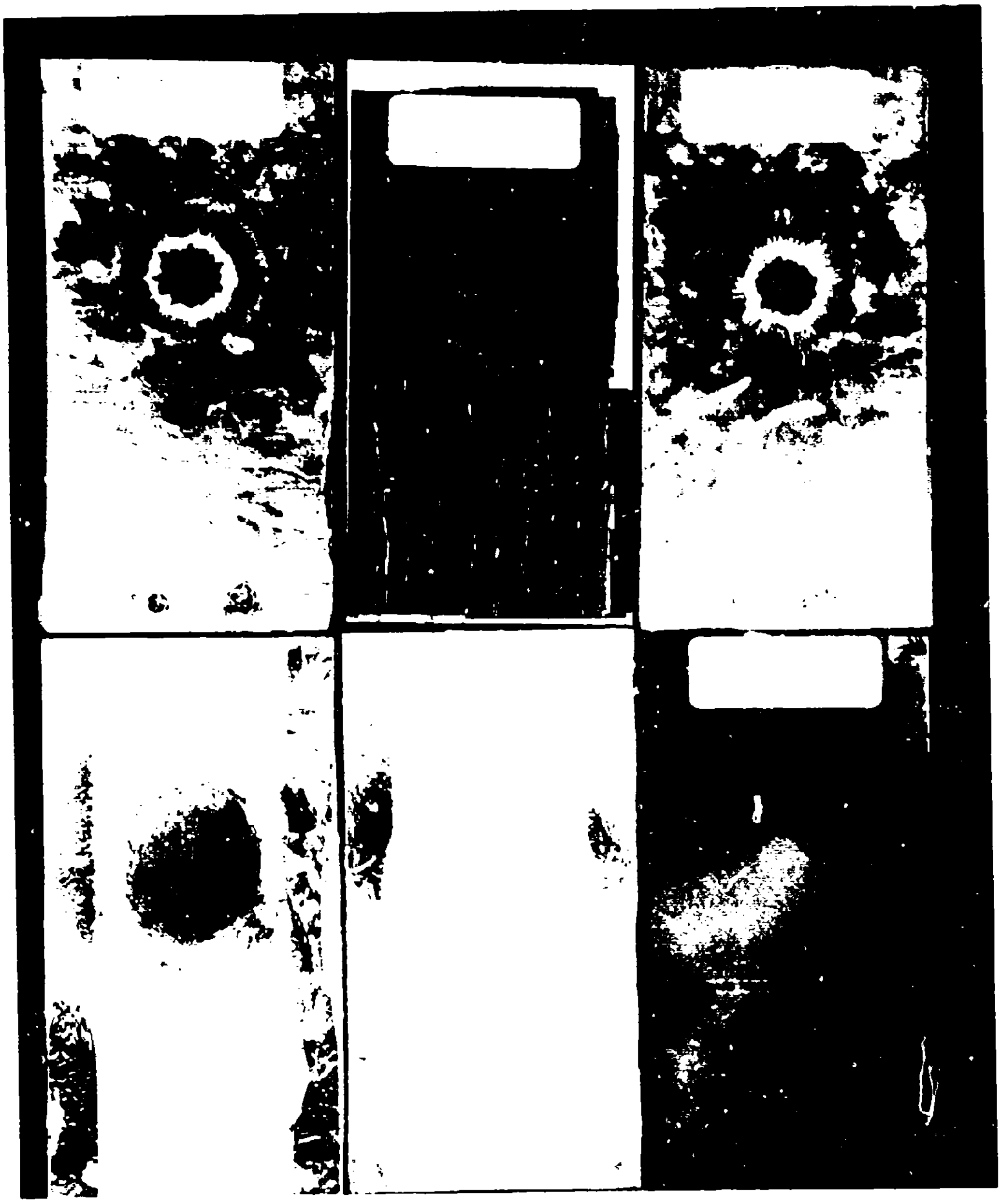


Figure A-26

103-BR43-AF03P-SE03 Figure A-25 November 20, 1969

This boron panel was first coated with a 2-mil silver filled epoxy and then two 3-mil aluminum strips were bonded on both sides of the 12-inch dimension of the panel. An 18 KV discharge was directed to this coated panel; the discharge current had a peak of 100 KA with a duration of 27 μs and a risetime of 14 μs.

A discolored coating and vaporized aluminum strips result. The back side of the substrate was slightly cracked, probably due to a collision with the discharge probe.

104-FG29-CM08C-0000 Figure A-25 November 20, 1969

This fiberglas panel was coated with an 8-mil micron copper filled epoxy paint over a 1-mil prime coat. A 20 KV discharge was directed to this coated panel. The discharge current was not recorded by the oscilloscope due to an early trigger; however, from the test results of Panel 109, the discharge current of this panel had a peak of approximately 100 KA with a duration of 31 μs.

No damage to the control panel was observed; the coating was discolored due to surface flashover.

105-FG30-CR04Z-0000 Figure A-26 November 21, 1969

This fiberglas panel was coated with 200 mesh phosphor-bronze wire fabric with no undercoating. The fabric was a plain weave utilizing 2.1-mil diameter wire and was bonded to the fiberglas panel with BMS 5-29A type 2 adhesive. The overall thickness of the coating was 4 mils. A 17 KV discharge was directed to this coated panel, the discharge current had a peak of 95 KA with a duration of 27 μs and a risetime of 14 μs.

No damage to the control panel was observed; however, the fabric was badly burned along the current path.

106-GP33-CR04Z-0000 Figure A-26 November 21, 1969

This graphite panel was coated with 200 mesh phosphor-bronze wire fabric with no undercoating. The fabric was a plain weave utilizing 2.1-mil diameter wire and was bonded to the graphite panel with BMS-29A type 2 adhesive. The overall thickness of the coating was 4 mils. An 18 KV discharge was directed to this coated panel; the discharge current had a peak of 100 KA with a risetime of 27 μs and a duration of 14 μs.

No damage to the substrate was observed even though the fabric coating was badly burned.

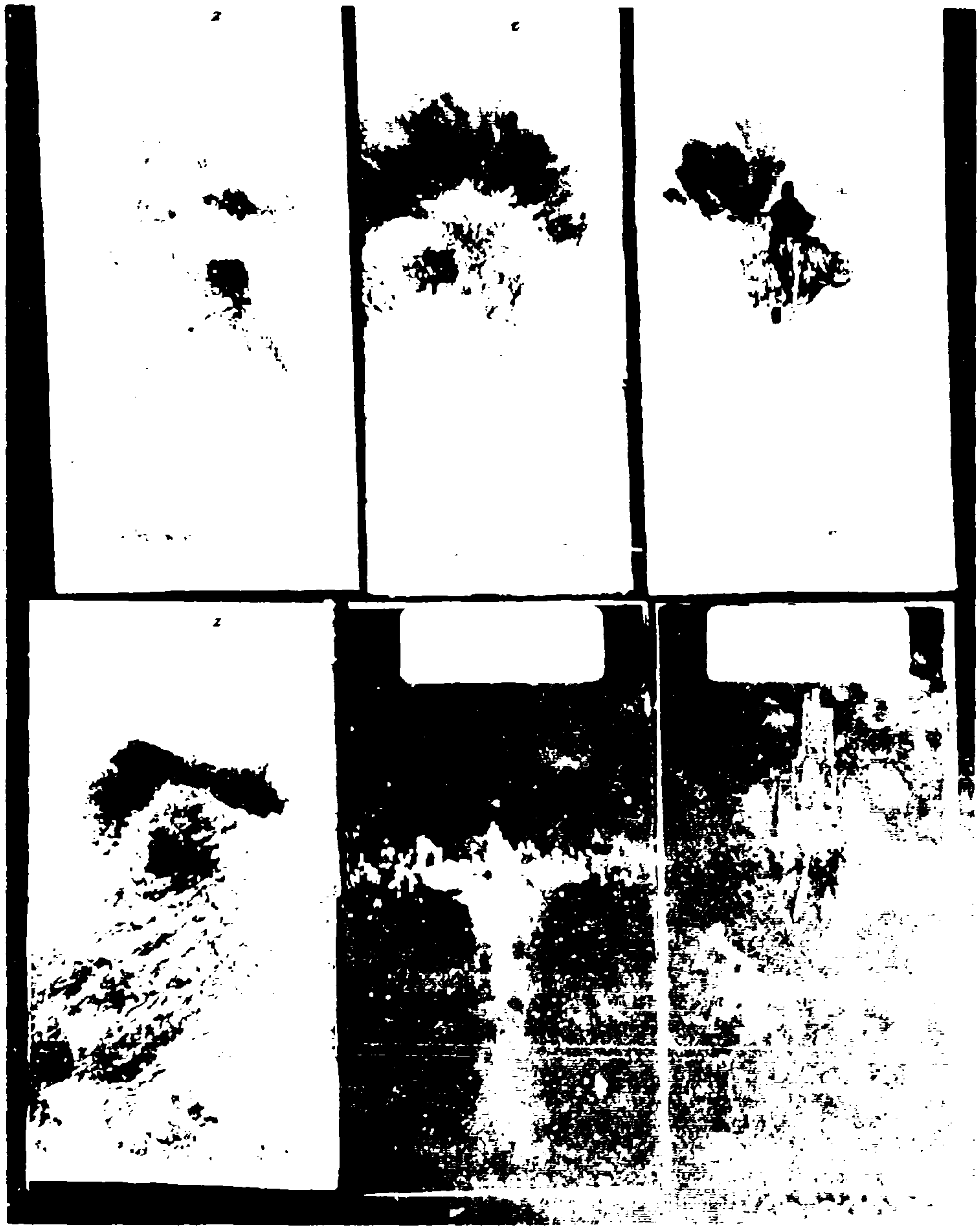


Figure A-26

107-BR44-CR04Z-0000 Figure A-26 November 21, 1969

This boron panel was coated with 200 mesh phosphor-bronze wire fabric with no undercoating. The fabric was a plain weave utilizing 2.1-mil diameter wire and was bonded to the boron panel with BMS-29A, type 2, adhesive. The overall thickness of the coating was 4 mils. An 18 KV discharge was directed to this coated panel; the discharge current had a peak of 98 KA with a risetime of 14 μs and a duration of 27 μs.

No damage to the substrate was observed even though the fabric coating was badly burned.

108-GP34-CK07C-0000 Figure A-26 November 21, 1969

This graphite panel was coated with a 7-mil 300 mesh purified copper powder filled silicone paint over a 1-mil prime coat. The copper filled silicone paint was applied by spraying. An 18 KV discharge was directed to this coated panel; the discharge current had a peak of 89 KA with a duration of 28 μs and a risetime of 14 μs.

The substrate was severely damaged, and it was also noted that most of the current actually discharged through the graphite fibers instead of the coating.

109-GP35-CM08C-0000 Figure A-26 November 24, 1969

This graphite panel was coated with an 8-mil micron copper powder filled epoxy paint over a 1-mil prime coat. An 18 KV discharge was directed to this coated panel; the discharge current had a peak of 83 KA with a duration of 30 μs and a risetime of 15 μs.

The substrate was severely damaged.

110-BR45-CM08C-0000 Figure A-26 November 21, 1969

This boron panel was coated with an 8-mil micron copper powder filled epoxy paint over a 1-mil prime coat. An 18 KV discharge was directed to this coated panel; the discharge current had a peak of 43 KA with a duration of 58 μs and a risetime of 18 μs.

The substrate was severely damaged.

111-FG31-SG12C-0000 Figure A-27 November 24, 1969

A No. 181 glass fabric saturated with silver filled epoxy paint was integrally bonded to this fiberglas panel. The overall thickness of the coating was 12 mils. An 18 KV discharge was directed to the coated panel; the discharge current had a peak of 90 KA with a risetime of 15 μs and a duration of 29 μs.

No damage to the control panel was observed; however, the silver-epoxy was badly burned.

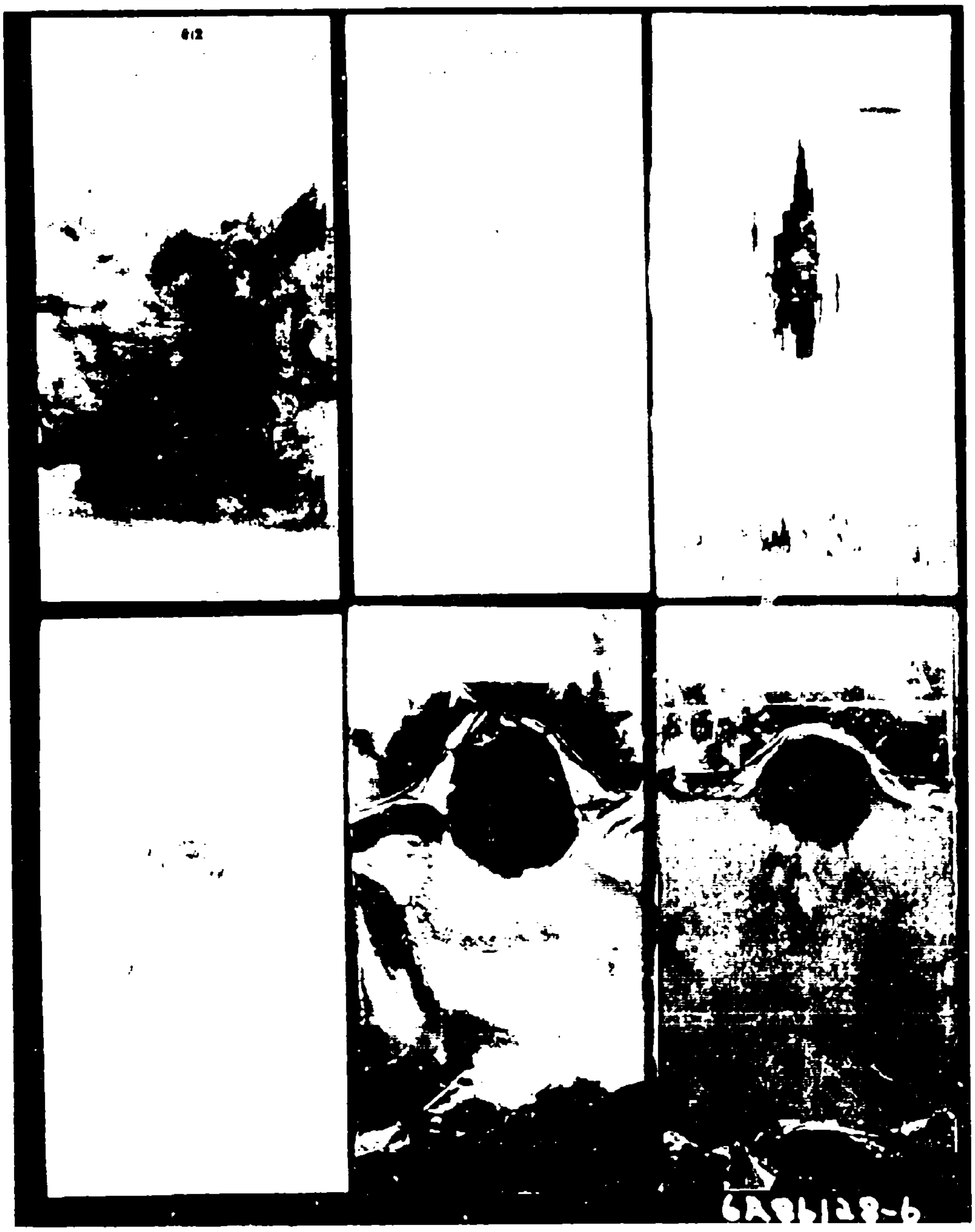


Figure A 27

112-FG32-AE05C-0000 Figure A-27 November 24, 1969
This fiberglas panel was coated with a 5-mil epoxy paint pigmented with 45 weight percent of 99.9 percent pure aluminum powder over a 1-mil prime coat. An 18 KV discharge was directed to this coated panel; the discharge current had a peak of 90 KA with a duration of 29 μs and a risetime of 15 μs.

No damage to the control panel was observed.

113-GP36-AE05C-0000 Figure A-27 November 24, 1969
This graphite panel was coated with a 5-mil epoxy paint pigmented with 45 weight percent of 99.9 percent pure aluminum powder over a 1 mil prime coat. An 18 KV discharge was initiated to this coated panel; the discharge current had a peak of 83 KA with a duration of 30 μs and a risetime of 15 μs.

The substrate was severely damaged.

114-BR46-AE05C-0000 Figure A-27 November 24, 1969
This boron panel was coated with a 5-mil epoxy paint pigmented with 45 percent, by weight, of 99.9 percent pure aluminum powder over a 1-mil prime coat. An 18 KV discharge was directed to this coated panel; the discharge current had a peak of 83 KA with a duration of 31 μs and a risetime of 16 μs.

The substrate was severely damaged.

115-GP37-NI0½C-0000 Figure A-27 December 16, 1969
A one-half mil nickel foil was integrally bonded to this graphite panel with no undercoating. A 17 KV discharge was directed to this coated panel; the discharge current had a peak of 100 KA with a risetime of 14 μs and a duration of 28 μs.

Most of the nickel foil was either vaporized or discolored. The front fiber matrix was severely burned; however, the panel was not punctured.

116-BR47-NI0½C-0000 Figure A-27 December 16, 1969
A one-half mil nickel foil was integrally bonded to this boron panel with no undercoating. A 17 KV discharge was directed to this coated panel; the discharge current was not recorded due to malfunction of the oscilloscope. However, from the results of the previous test, the current of this discharge was likely to be 100 KA with a risetime of 14 μs and a duration of 28 μs.

The nickel foil was almost completely vaporized, but no visual damage to the substrate was observed.

117-GP38-ME02C-0000 Figure A-28 December 15, 1969

This graphite panel was coated with a 2-mil Araldite 488E32 thermoplastic epoxy paint filled with 50 percent (by weight) Sterling MTNS carbon black; no undercoating was applied. MTNS is a thermal carbon with moderate resistivity. An 18 KV discharge was directed to this coated panel; the discharge current had a peak of 89 KA with a risetime of 14 μs and a duration of 29 μs.

The substrate was severely damaged.

118-BR48-AR04Z-0000 Figure A-28 December 17, 1969

BMS 5-29A, type 2 adhesive, was used to bond 200 mesh 5056 aluminum wire fabric to this boron panel with no undercoating. The fabric was a twilled weave with a wire diameter of 2.1 mils. An 18 KV discharge was directed to this coated panel; the discharge current had a peak of 111 KA with a risetime of 15 μs and a duration of 26 μs.

No damage to the substrate was observed.

119-BR49-LK14C-0000 Figure A-28 December 16, 1969

This boron panel was coated with 45 percent (by weight) aluminum trifluoride (Al_2F_6) in Dow Corning 92-009 silicone. This 14-mil coating was applied over a one-mil prime coat. The crowbar switch was disconnected from the simulator; a 20 KV discharge was then directed to this coated panel, but the underdamped oscillatory discharge was not recorded. Compared to the results of previous tests, it was estimated that the current was approximately 50 KA for this test.

The substrate was severely damaged.

120-GP39-LK14C-0000 Figure A-28 December 16, 1969

This graphite panel was coated with 45 percent (by weight) aluminum trifluoride (Al_2F_6) in Dow Corning 92-009 silicone. This 14-mil coating was applied over a one-mil prime coat. A 20 KV discharge was directed to this coated panel; the discharge current had a peak of 87 KA with a risetime of 15 μs and a duration of 32 μs.

The substrate was severely damaged.

121-GP40-SG12C-0000 Figure A-28 December 16, 1969

A 181E glass fabric impregnated with silver filled epoxy was integrally bonded to this graphite panel to provide a 12-mil coating; no undercoating was applied. A 20 KV discharge was directed to this coated panel; the discharge current had a peak of 97 KA with a risetime of 14 μs and a duration of 28 μs.

No visual damage to the substrate was observed; however, the epoxy-matrix was discolored. The glass fabric was partly delaminated from the substrate.

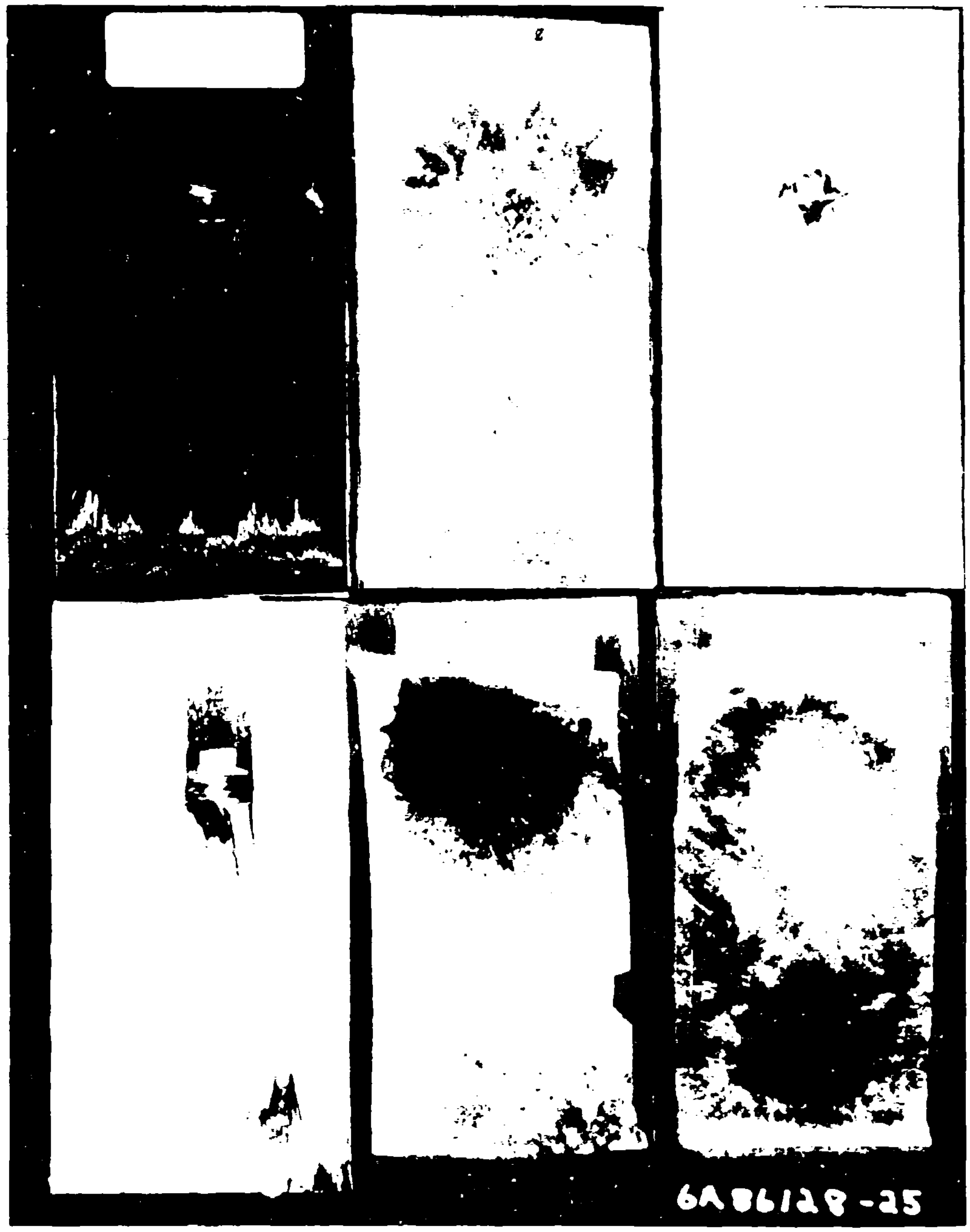


Figure A-28

122-BR50-SG12C-0000 Figure A-28 December 17, 1969

A 181E glass fabric impregnated with silver filled epoxy was integrally bonded to this boron panel to provide a 12-mil coating; no undercoating was applied. An 18 KV discharge was initiated to this coated panel; the discharge current had a peak of 95 KA with a risetime of 16 μs and a duration of 28 μs.

The coating was discolored and wrinkled; the back side of the substrate was slightly cracked and a possible collision mark between the discharge probe and front surface was observed.

123-FG33-AR04Z-0000 Figure A-29 December 17, 1969

BMS 5-29A, type 2 adhesive was used to bond 200 mesh 5056 aluminum wire fabric to this fiberglas panel with no undercoating. The fabric was a twilled weave with a wire diameter of 2.1 mil. A 16 KV discharge was directed to this coated panel; the peak current was 102 KA with a risetime of 14 μs and a duration of 26 μs.

No damage to the control panel was observed.

124-GP41-AR04Z-0000 Figure A-29 December 17, 1969

BMS 5-29A, type 2 adhesive was used to bond 200 mesh 5056 aluminum wire fabric to this graphite panel with no undercoating. The fabric was a twilled weave with a wire diameter of 2.1-mil. A 17 KV discharge was directed to this coated panel; the peak current was 107 KA with a risetime of 14 μs and a duration of 26 μs.

No damage to the substrate was observed.

125-BR51-ME02C-0000 Figure A-29 December 17, 1969

This boron panel was coated with a 2-mil epoxy filled 50 percent (by weight) sterling MTNS carbon black. No undercoating was applied. MTNS is a thermal carbon with moderate resistivity. An 18 KV discharge was initiated to this coated panel; the peak current was 39 KV with a rise time of 16 μs and a duration of 52 μs.

The substrate was severely damaged, most of the coating bubbled.

126-FG34-AE07C-0000 Figure A-29 December 17, 1969

This fiberglas panel was coated with 325 mesh aluminum powder (99.9 percent purity) sandwiched between an epoxy primer and an EPON 1001 top coat for a total thickness of 7 mils. The crowbar switch was disconnected from the simulator; the 20 KV discharge as directed to this coated panel yielded an underdamped oscillatory discharge with a peak current of 105 KA and a ringing frequency of 23 kHz.

No damage to the control panel was observed; however, the coating was badly melted.

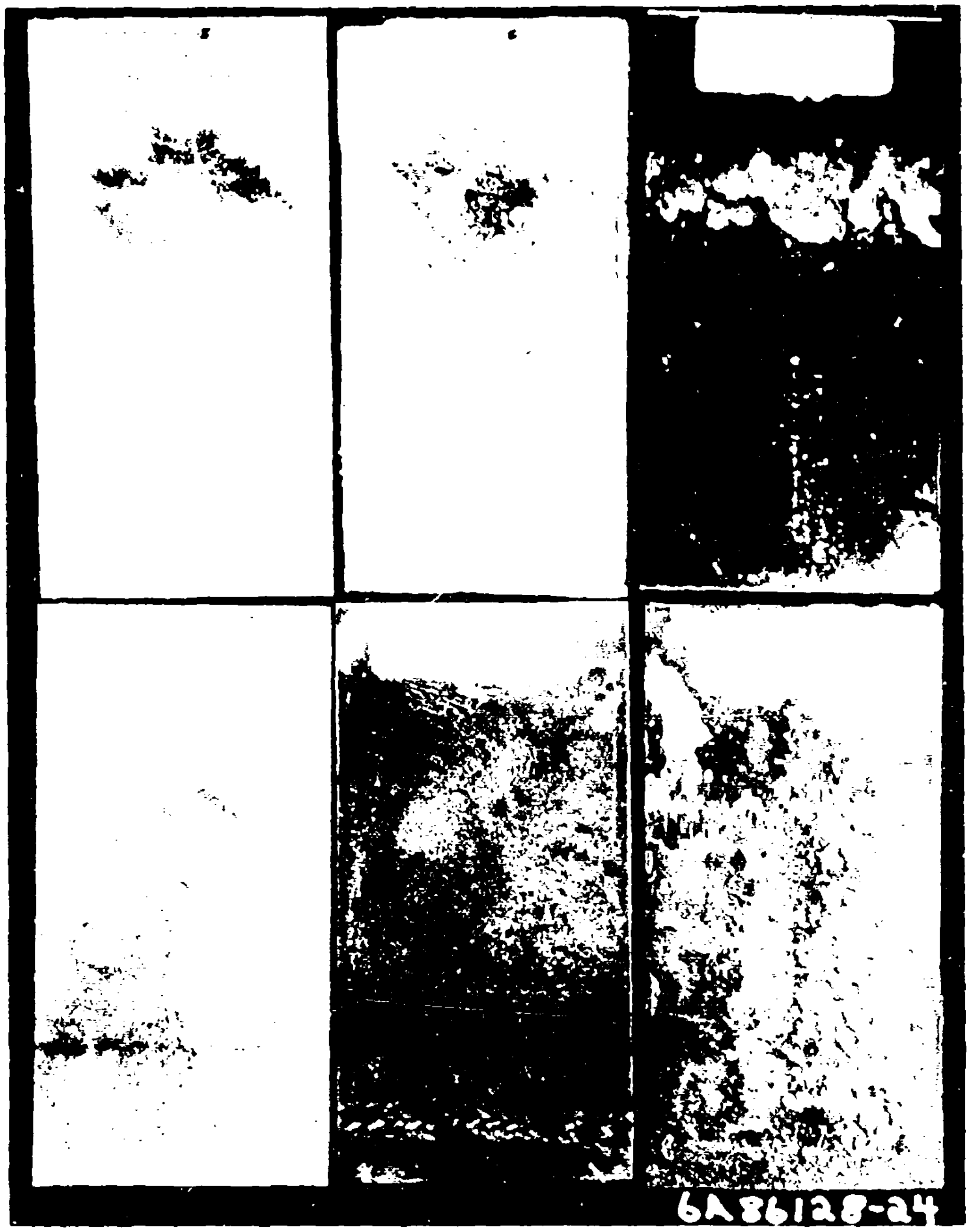


Figure A-29

127-FG35-CE08C-0000 Figure A-29 December 17, 1969

This fiberglas panel was coated with approximately 300 mesh, 99.9 percent purity copper powder sandwiched between an epoxy primer and an EPON 1001 top coat for an 8-mil total thickness. The capacitor bank, due to the extremely high impedance of the coating, failed to discharge even at a 25 KV charged voltage; however, streamer type arcs were intensively radially discharged.

No damage to the coated panel was observed; however, the coating was burned and wrinkled.

128-BR52-CE09C-0000 Figure A-29 December 17, 1969

This boron panel was coated with approximately 300 mesh, 99.9 percent purity copper powder sandwiched between an epoxy primer and an EPON 1001 top coat for a 9-mil total thickness. A 25 KV discharge was directed to this coated panel; the discharge current had a peak of 72 KA with a risetime of 16 μs and a duration of 52 μs.

The substrate was severely damaged and the coating was badly melted.

129-GP42-CE11C-0000 Figure A-30 December 18, 1969

This graphite panel was coated with approximately 300 mesh 99.9 percent purity copper powder sandwiched between an epoxy primer and an EPON 1001 top coat for a total thickness of 11 mils. A 25 KV discharge was initiated to this coated panel; the discharge current had a peak of 122 KA with a risetime of 15 μs and a duration of 33 μs.

The substrate was severely damaged.

130-GP43-CE09C-KF03 Figure A-30 December 18, 1969

Copper powder sandwiched between an epoxy primer and an EPON 1001 top coat was coated on this graphite panel over a 3-mil Kapton film undercoating. A 25 KV discharge was directed to this 9-mil coating; the discharge current had a peak of 122 KA with a risetime of 15 μs and a duration of 33 μs.

The substrate was damaged at the edges only.

131-GP44-AE10C-0000 Figure A-30 December 18, 1969

This graphite panel was coated with 325 mesh 99.9 percent purified aluminum powder sandwiched between an epoxy primer and an EPON 1001 top coat for a total thickness of 10 mils. A 17 KV discharge was directed to this coated panel; the discharge current had a peak of 84 KA with a risetime of 14 μs and a duration of 31 μs.

The substrate was severely damaged.

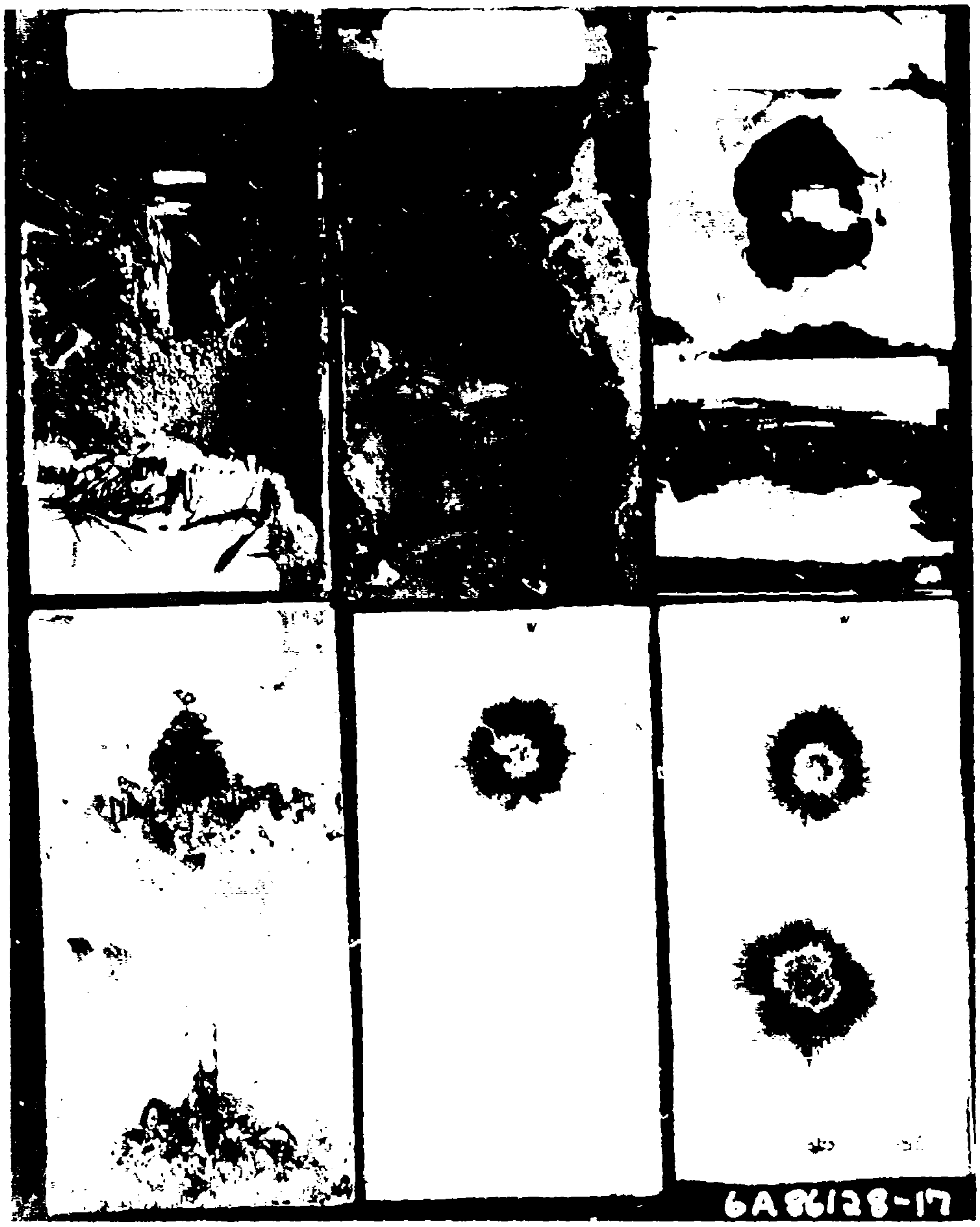


Figure A-30

132-BR53-AE12C-0000 Figure A-30 December 18, 1969

This boron panel was coated with 325 mesh 99.9 percent purified aluminum powder sandwiched between an epoxy primer and an EPON 1001 top coat for a total thickness of 12 mils. A 17 KV discharge was directed to this coated panel; the peak current was 48 KA with a risetime of 18 μs and a duration of 54 μs.

The substrate was severely damaged and the coating was badly melted.

133-FG36-AR16W-0000 Figure A-30 January 5, 1970

This fiberglas panel was coated with 60 mesh 5056 aluminum fabric. No undercoating was applied. The aluminum fabric was a twilled weave utilizing 8-mil diameter wire and bonded to the fiberglas panel with BMS 5-29A type 2 adhesive. The total thickness of the coating was about 16 mils. A 16 KV discharge was directed to this coated panel; the discharge current had a peak of 104 KA with a risetime of 15 μs and a duration of 26 μs.

No damage to the control panel was observed.

134-BR54-AR16W-0000 Figure A-30 January 5, 1970

This boron panel was coated with 60 mesh 5056 aluminum fabric. No undercoating was applied. The aluminum fabric was a twilled weave utilizing 8-mil diameter wire and bonded to this boron panel with BMS 5-29A type 2 adhesive. The total thickness of the coating was about 16 mils. Two 16 KV discharges were directed to this coated panel. The first discharge was crowbarred at the time of the peak current due to the early triggered ignition. The second discharge had a peak current of 104 KA with a risetime of 15 μs and a duration of 26 μs.

No damage to the substrate from either discharge was observed.

135-GP45-AR16W-0000 Figure A-31 January 6, 1970

A 16 mil-60-mesh 5056 aluminum fabric was adhesively bonded to this graphite panel with BMS 5-29A type 2 adhesive. No undercoating was applied. The fabric was a twilled weave utilizing 8-mil diameter wire. A 16 KV discharge was initiated to this coated panel; the discharge current had a peak of 105 KA with a risetime of 15 μs and a duration of 26 μs.

No visible damage to the substrate was observed.

136-FG37-AR16P-0000 Figure A-31 January 6, 1970

This fiberglas panel was partially covered with 60 mesh 5056 aluminum fabric. No undercoating was applied The fabric, a twilled weave utilizing 8-mil diameter wire, was adhesively bonded to the test panel in the following manners: 1-inch wide strip on the four sides and 1/2 inch wide strip at the center along the 12-inch dimension direction.

A 17 KV discharge was directed to this coated panel; the discharge current had a peak of 106 KA with a risetime of 15 μs and a duration of 28 μs.

No damage to the control panel was observed; the center strip was vaporized.

137-GP46-AR16P-0000 Figure A-31 January 6, 1970

This graphite panel was partially covered with 60 mesh 5056 aluminum fabric. No undercoating was applied. The fabric, a twilled weave utilizing 8-mil diameter wire, was adhesively bonded to the test panel in the following manner: 1-inch wide strip on the four sides and 1/2 inch wide strip at the center along the 12-inch dimension direction. A 17 KV discharge was directed to this coated panel; the discharge current had a peak of 106 KA with a risetime of 13 μs and a duration of 25 μs.

The front surface of the substrate was badly burned. The center strip was vaporized.

138-BR55-AR16P-0000 Figure A-31 January 6, 1970

This boron panel was partially covered with 60 mesh 5056 aluminum fabric. No undercoating was applied. The fabric, a twilled weave utilizing 8-mil diameter wire, was adhesively bonded to the test panel in the following manner: 1-inch wide strip along the four sides and a 1/2 inch strip at the center along the 12-inch dimension direction. A 17 KV discharge was directed to this coated panel; the discharge current had a peak of 106 KA with a risetime of 15 μs and a duration of 27 μs.

No damage to the substrate was observed. The center strip was vaporized.

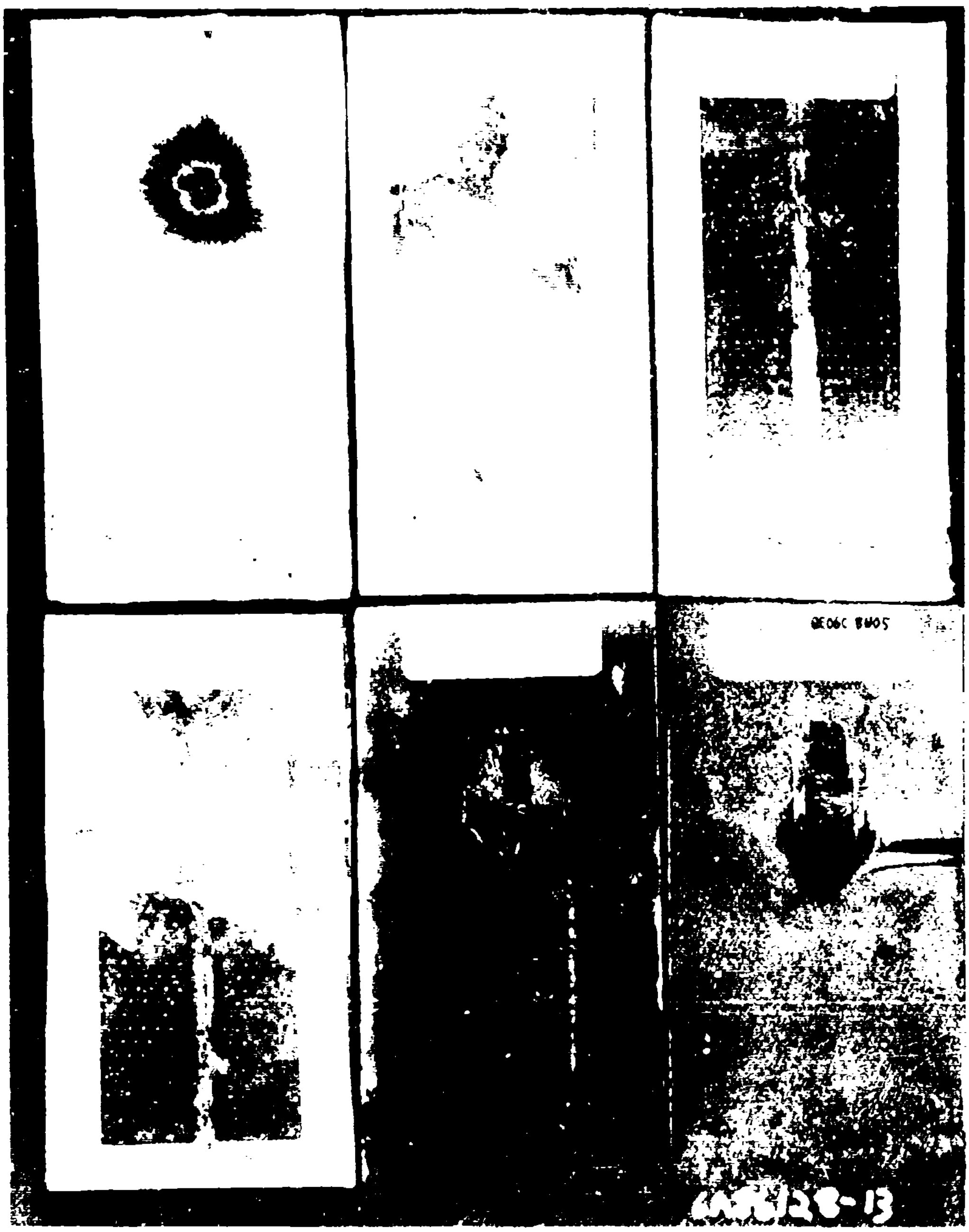
139-GP47-QE07C-0000 Figure A-31 January 6, 1970

This graphite panel was coated with a 7-mil Araldite 488E32 thermoplastic epoxy paint filled with aluminum powder and MTNS carbon black. No undercoating was applied. The aluminum powder is 325 mesh 99.9 percent purity; the MTNS carbon black is a thermal carbon with a moderate resistivity. An 18 KV discharge was directed to this coated panel; the discharge current had a peak of 97 KA with a risetime of 15 μs and a duration of 29 μs.

The substrate was severely damaged.

140-GP46-QE06C-BN09 Figure A-31 January 6, 1970

This graphite panel was coated with a 6-mil Araldite 488E32 thermoplastic epoxy paint which was filled with 325 mesh, 99.9 percent pure aluminum powder and MTNS carbon black, a thermal carbon with a moderate resistivity. A 5-mil undercoat of 45 percent boron nitride in the same epoxy



was employed. An 18 KV discharge was directed to this coated panel; the discharge current had a peak of 93 KA with a risetime of 15 μs and a duration of 29 μs.

The substrate was severely damaged.

141-GP49-XE12C-0000 Figure A-32 January 6, 1970

This graphite panel was coated with Araldite epoxy paint filled with MTNS carbon black, a thermal carbon with a moderate resistivity. Then the coating was hand sprinkled with lithium chloride. The total coating thickness was 11.6 mils. An 18 KV discharger was directed to this coated panel; the discharge current was 93 KA with a risetime of 14 μs and a duration of 28 μs.

The substrate was severely damaged and the coating surface was found wet.

142-GP50-YE09C-BN03 Figure A-32 January 6, 1970

This graphite panel was coated with a 9 mil Araldite 488E32 thermoplastic epoxy paint which was filled with aluminum trifluoride and MTNS carbon black, a thermal carbon with a moderate resistivity. A 3-mil undercoat of boron nitride filled epoxy was used. An 18 KV discharge was directed to this coated panel; the discharge current had a peak of 93 KA with a risetime of 14 μs and a duration of 28 μs.

The substrate was severely damaged.

143-BR56-XE11C-0000 Figure A-32 January 6, 1970

This boron panel was coated with Araldite thermoplastic epoxy paint filled with MTNS carbon black; a thermal carbon with a moderate resistivity. Then the coating was hand sprinkled with lithium chloride. The total coating thickness was 11 mils. An 18 KV discharge was directed to this coated panel; the discharge current had a peak of 47.5 KA with a risetime of 17 μs and a duration of 52 μs.

The panel was severely damaged. The coating was badly burned.

144-BR57-QE07C-0000 Figure A-32 January 7, 1970

This boron panel was coated with a 7-mil Araldite 488E32 thermoplastic epoxy paint filled with aluminum and carbon black. No undercoating was applied. The aluminum was 325 mesh 99.9 percent purified powder, and the carbon was MTNS carbon black, a thermal carbon with a moderate resistivity. An 18 KV discharge was directed to this coated panel; the discharge current was 82 KA with a risetime of 18 μs and a duration of 33 μs.

The substrate was severely damaged and the coating was badly burned.


BE66C 3N05
99 BN03

145-BR58-QE06C-BN05 Figure A-32 January 7, 1970

This boron panel was coated with a 6-mil Araldite 488E32 thermoplastic epoxy paint which was filled with 325 mesh 99.9 percent pure aluminum powder and MTNS carbon black, a thermal carbon with a moderate resistivity. A 5-mil boron nitride filled epoxy undercoating was employed. An 18 KV discharge was directed to this panel; the discharge current had a peak of 75 KA with a risetime of 21 μs and a duration of 35 μs.

The substrate was severely damaged and cracked.

146-BR59-YE09C-BN03 Figure A-32 January 7, 1970

This boron panel was coated with a 9-mil Araldite 488E32 thermoplastic epoxy paint which was loaded with aluminum trifluoride and MTNS carbon black, a thermal carbon with a moderate resistivity. A 3-mil boron nitride filled epoxy undercoat was applied. An 18 KV discharge was directed to this coated panel; the discharge current had a peak of 42 KA with a risetime of 17 μs and a duration of 52 μs.

The substrate was severely damaged and the coating was badly deteriorated.

147-FG38-QE07C-0000 Figure A-33 January 7, 1970

This fiberglas panel was coated with a 7-mil Araldite 488E32 thermoplastic epoxy paint filled with aluminum and carbon. No undercoating was applied. The aluminum was 325 mesh 99.9 percent purified powder, and the carbon was MTNS carbon black, a thermal carbon with a moderate resistivity. An 18 KV discharge was directed to this coated panel; the discharge current had a peak of 94 KA with a risetime of 16 μs and a duration of 30 μs.

No damage to the control panel was observed; however, the coating was badly deteriorated.

148-FG39-YE09C-BN03 Figure A-33 January 7, 1970

This fiberglas panel was coated with a 9-mil Araldite 488E32 thermoplastic epoxy paint which was loaded with aluminum trifluoride and MTNS carbon black, a thermal carbon with a moderate resistivity. A 3-mil boron nitride filled epoxy undercoat was applied. An 18 KV discharge was directed to this coated panel; the discharge current waveform was not recorded, however, it was estimated to be 90 KA with a duration 28 μs.

No damage to the control panel was observed.

149-FG40-QE06C-BN05 Figure A-33 January 7, 1970

This fiberglas panel was coated with a 6-mil Araldite 488E32 thermoplastic epoxy paint which was filled with 325 mesh 99.9 percent pure aluminum powder and MTNS carbon black, a thermal carbon with a moderate resistivity. A 5-mil boron nitride filled epoxy undercoat was employed.

Figure A 22

An 18 KV discharge was directed to this coated panel; the discharge current had a peak of 97 KA with a risetime of 15 μs and a duration of 28 μs.

No damage to the control panel was observed.

150-FG41-XE11C-0000 Figure A-33 January 7, 1970
This fiberglas panel was coated with Araldite thermoplastic epoxy paint filled with MTNS carbon black, a thermal carbon with a moderate resistivity. Then the undercoating was hand sprinkled with lithium chloride. The total coating thickness was 11 mils. An 18 KV discharge was directed to this coated panel; the discharge current waveform was not recorded, however, it was estimated to be 90 KA with a duration of 28 μs.

No damage to the control panel was observed.

151-BR60-00000-ALCO Figure A-33 January 7, 1970
This was a composite sandwich panel. A one-half inch thick aluminum honeycomb core was bonded between a fiberglas panel and a boron panel. An 18 KV discharge was initiated to the boron substrate side; the discharge current had a peak of 108 KA with a risetime of 15 μs and a duration of 28 μs.

The boron substrate was punctured and a large area of honeycomb core under the discharge probe was vaporized.

152-GP51-00000-ALCO Figure A-33 January 7, 1970
This was a composite sandwich panel. A one-half inch aluminum honeycomb core was bonded between a fiberglas panel and a graphite panel. An 18 KV discharge was directed to the graphite substrate side; the discharge current has a peak of 110 KA with a risetime of 15 μs and a duration of 28 μs.

The front surface of the graphite substrate was burned but not punctured.

153-FG39-00000-ALCO Figure A-34 January 8, 1970
This was a composite sandwich panel. A one-half inch aluminum honeycomb core was bonded between two fiberglas panels. The crowbar switch was disconnected from the simulator. A 30 KV underdamped oscillatory discharge was directed to the honeycomb core where a one-half inch diameter hole was cut on fiberglas panel. It was found that the dielectric strength of the 1/16-inch thick fiberglas will prevent a 30 KV discharge. The oscillatory discharge had a peak of 158 KA with a ring frequency of 20 kHz.

The two fiberglas panels were separated from the honeycomb core and a roughly 5-inch diameter hole was open on the honeycomb core.

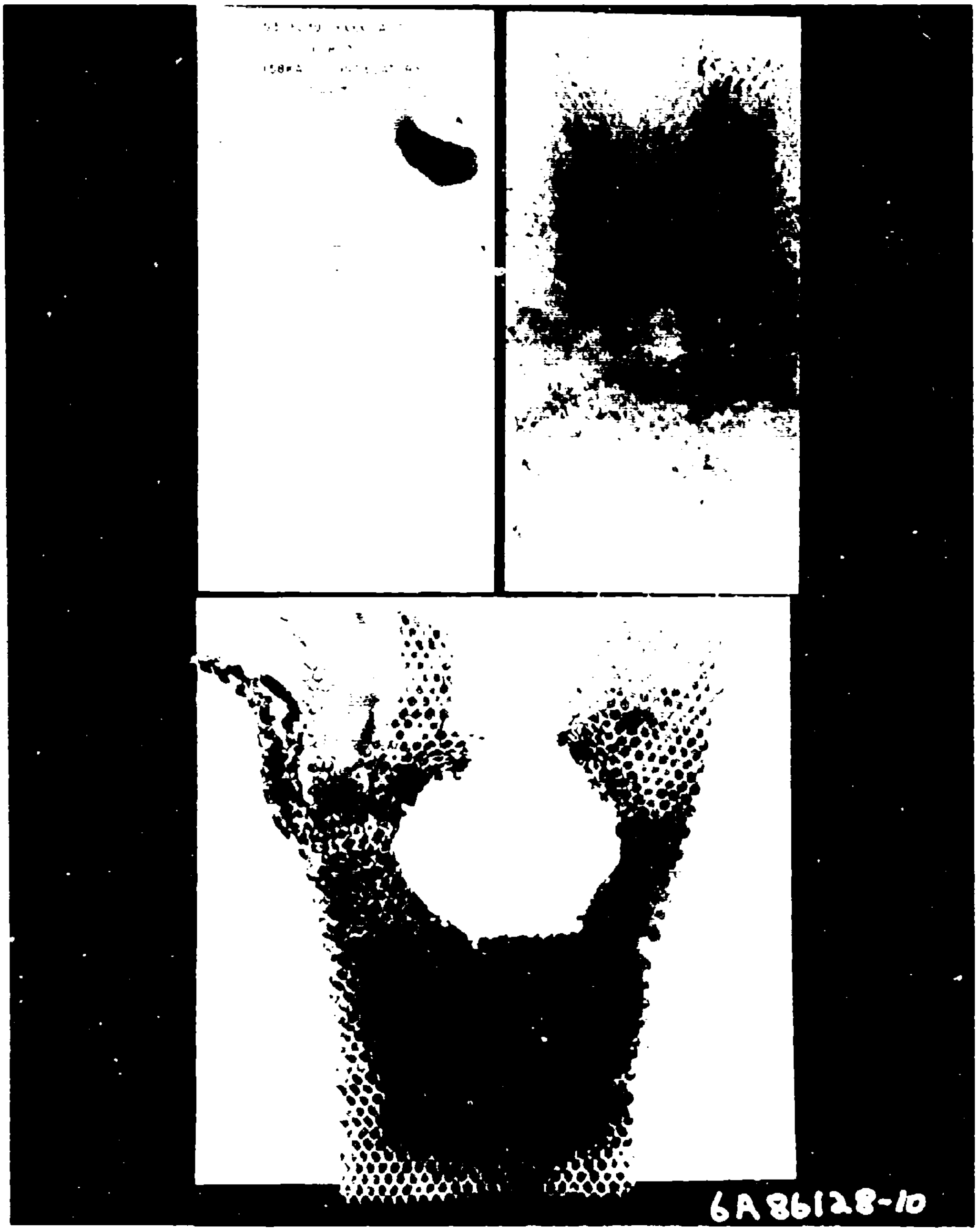


Figure A-34

154-GP52-N101C-0000 Figure A-35 February 25, 1970

This graphite panel was coated with a 1-mil nickel foil; no undercoating was applied. A 14.5 KV discharge was initiated to this test panel; the discharge current had a peak of 105 KA with a risetime of 14 μs and a duration of 27 μs.

The front surface of the graphite substrate was slightly charred. The size of a burned off area of the nickel foil was comparable to that of the previously tested one mil aluminum foil.

155-BR61-UE05C-0000 Figure A-35 February 25, 1970

This boron panel was coated with a 5-mil EPON 1001 epoxy paint filled with XC-72, a highly conductive carbon black powder. No other undercoating was applied. A 16.5 KV discharge was directed to this coated panel. The current waveform was not recorded due to a malfunction of the oscilloscope; however, the current was estimated to be 50 KA with a duration of 50 μs.

The substrate was severely damaged.

156-BR62-UE05C-KF01 Figure A-35 February 25, 1970

This boron panel was coated with a 5-mil EPON 1001 epoxy paint filled with XC-72, a highly conductive carbon black. This coating was applied over an underlayer of a one-mil Kapton film. A 17 KV discharge was directed to this coated panel. The discharge current had a peak of 50 KA with a duration of 50 μs.

The substrate was severely damaged.

157-BR63-UE05T-KF01 Figure A-35 February 25, 1970

This boron panel with an undercoating of a 1-mil Kapton film was coated with a 5-mil EPON 1001 epoxy paint filled with XC-72, a highly conductive carbon black powder. In addition, two aluminum diverter strips were also attached to the 12-inch dimension edges. A 17 KV discharge was directed to this coated panel; the discharge had a peak current of 90 KA with a risetime of 20 μs and a duration of 38 μs.

The substrate was severely damaged.

158-GP53-UE05T-KF01 Figure A-35 February 25, 1970

This graphite panel with an undercoating of a 1-mil Kapton film was coated with a 5-mil EPON 1001 epoxy paint loaded with XC-72, a highly conductive carbon black powder; also, two aluminum diverter strips were bonded to the 12-inch dimension edges. A 16 KV discharge was directed to this coated panel. The discharge current had a peak of 100 KA with a risetime of 13.5 μs and a duration of 26 μs.

The substrate was severely damaged.


6A86366-19

159-FG43-UE05C-0000 Figure A-35 February 26, 1970
This fiberglas panel was coated with an epoxy paint filled with XC-72. The oscillatory, 16 KV discharge had a peak current of 120 KA with a ring frequency of 34.5 KHz.

No damage to the panel was observed.

160-BR64-DE10C-BN06 Figure A-36 February 26, 1970
A 10-mil epoxy paint filled with potassium nitrate (KNO_3) was applied over an undercoating of a 6-mil epoxy filled with boron nitride (BN).

An 18 KV discharge was directed to this panel. The discharge current had a peak of 50 KA with a risetime of 16 μs and a duration of 52 μs.

The substrate was severely damaged.

161-BR65-DE10C-KT01 Figure A-36 February 26, 1970
This boron panel was coated with a composite coating system consisting of a 10-mil EPON 1001 epoxy paint filled with potassium nitrate (KNO_3) and an undercoating of a one-mil Kapton film. An 18 KV discharge was directed to this panel. The discharge current had a peak of 44 KA with a risetime of 16 μs and a duration of 52 μs.

The substrate was damaged; however, it was less than that of the previous panel (No. 160).

162-FG44-UE05T-0000 Figure A-36 February 26, 1970
This fiberglas panel was coated with a 5-mil EPON 1001 epoxy paint filled with XC-72. No undercoating was applied. Two aluminum diverter strips were attached to the 12-inch edges. A 16 KV discharge was directed to this panel. The discharge current had a peak of 100 KA with a ring frequency of 25.6 KHz. No damage to the panel was observed.

163-BR66-DE10C-0000 Figure A-36 February 26, 1970
This boron panel was coated with a 10-mil EPON 1001 epoxy paint filled with potassium nitrate (KNO_3). No undercoating was applied. A 16 KV discharge was directed to this panel. The discharge current had a peak of 50 KA with a risetime of 15 μs and a duration of 50 μs.

The substrate was severely damaged.

164-BR67-UE05T-0000 Figure A-36 February 26, 1970
This boron panel was coated with a 5-mil EPON 1001 epoxy paint filled with XC-72. Aluminum strips were attached along the 12-inch edges of the panel. An 18 KV oscillatory discharge was directed to the panel. The discharge current had a peak current of 100 KA and a ring frequency of 26.5 KHz.

The substrate was severely damaged.

Figure A-36

165-BR68-DE10T-BN06 Figure A-36 February 26, 1970

A 10-mil EPON 1001 epoxy paint filled with potassium nitrate (KNO_3) was applied over an undercoating of a 6-mil epoxy paint filled with boron nitride (BN). Aluminum strips were attached to the panel on 12-inch edges. The discharge current had a peak of 102 KA, a risetime of 15 μs, and a duration of 28 μs.

The substrate was severely damaged.

166-BR69-DE10T-0000 Figure A-37 February 26, 1970

This boron panel was coated with a 10-mil EPON 1001 epoxy paint filled with potassium nitrate (KNO_3). Aluminum strips were also attached to the 12-inch edges. An 18 KV discharge was directed to this coated panel. The discharge current had a peak of 110 KA with a risetime of [illegible] μs and a duration of 28 μs.

The substrate was severely damaged.

167-BR70-DE10T-KF01 Figure A-37 February 26, 1970

This boron panel was coated with a 10-mil EPON 1001 epoxy paint filled with potassium nitrate (KNO_3) over an undercoating of a 1-mil Kapton film. Two aluminum diverter strips were attached to the 12-inch edges. A 17 KV discharge was directed to this panel. The discharge current had a peak of 104 KA with a risetime of 13 μs and a duration of 27 μs.

No visible damage to the substrate was observed; the hole punctured on the left side was probably caused by the collision of the panel to the holding bracket. A surface flash over pattern was shown.

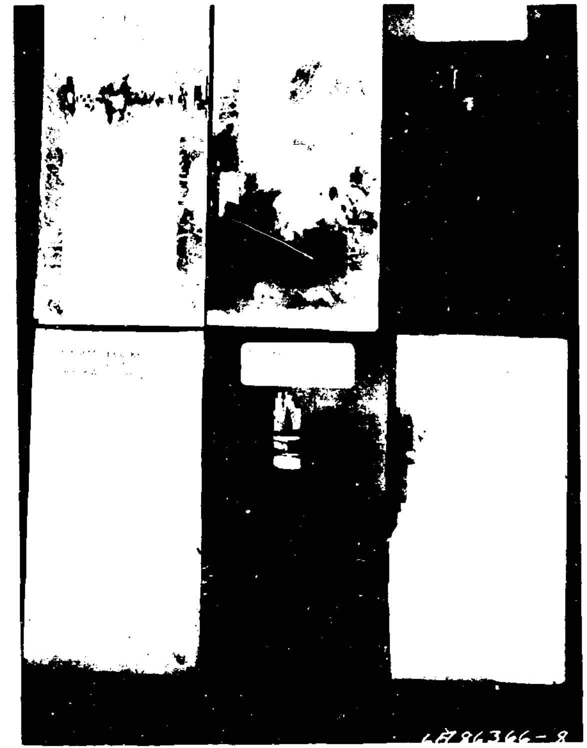
168-GP54-UE05C-KF01 Figure A-37 February 26, 1970

A 5-mil EPON 1001 epoxy paint filled with XC-72, a highly conductive carbon black, was coated over an undercoating of a 1-mil Kapton film to this graphite substrate. A 16 KV discharge was directed to this coated panel. The discharge current had a peak of 92 KA with a risetime of 17 μs and a duration of 31 μs.

The substrate was severely damaged.

169-GP55-DE10C-KF01 Figure A-37 February 26, 1970

This graphite panel was coated with a 10-mil EPON 1001 epoxy paint filled with potassium nitrate (KNO_3) over an undercoating of a one-mil Kapton film. A 17 KV discharge was directed to this coated panel. The discharge had a peak current of 83 KA with a risetime of 16 μs and a duration of 35 μs.



No visible damage to the substrate around the neighboring area of the discharge probe was observed; however, the fibers along the edge closest to the discharge probe were damaged and delaminated as the discharge arc was forced to flash over the coating surface and re-attached to the closest edge.

170-GP56-UE05C-0000 Figure A-37 February 27, 1970

This graphite panel with no undercoating was coated with a 5-mil EPON 1001 epoxy paint filled with XC-72, a highly conductive carbon black. A 17 KV discharge was directed to this coated panel. The discharge current had a peak of 98 KA with a risetime of 16 μs and a duration of 30 μs.

The substrate was severely damaged

171-GP57-DE10C-0000 Figure A-37 February 27, 1970

This graphite panel was coated with a 10-mil EPON 1001 epoxy paint filled with potassium nitrate (KNO_3); no undercoating was applied. An 18 KV discharge was directed to this coated panel. The discharge had a peak current of 94 KA with a risetime of 16 μs and a duration of 34 μs.

No visible damage to the substrate around the neighboring area of the discharge probe was observed; however, the fibers along the edge closest to the discharge probe were damaged and delaminated as the discharge arc was forced to flash over the coating surface and re-attached to the closest edge.

172-GP58-DE10C-BN06 Figure A-38 February 27, 1970

A composite coating system consisted of a 10-mil EPON 1001 epoxy paint filled with potassium nitrate (KNO_3) and an undercoating of a 5.7-mil epoxy paint filled with boron nitride (BN) was applied to this graphite panel. A 17 KV discharge was directed to this coated panel. The discharge current had a peak of 100 KA with a risetime of 15 μs and a duration of 30 μs.

The substrate was severely damaged.

173-GP59-DE10T-BN06 Figure A-38 February 27, 1970

A composite coating system consisted of diverter strips, a surface coating, and an undercoating was applied to this graphite panel. The surface coating was a 10-mil EPON 1001 epoxy paint loaded with potassium nitrate (KNO_3), the undercoating was a 6-mil epoxy paint filled with boron nitride (BN), and two diverter strips attached to the 12-inch dimension edges. A 17 KV discharge was directed to this coated panel, the discharge current had a peak of 104 KA with a risetime of 15 μs and a duration of 29 μs.

The substrate was severely damaged.

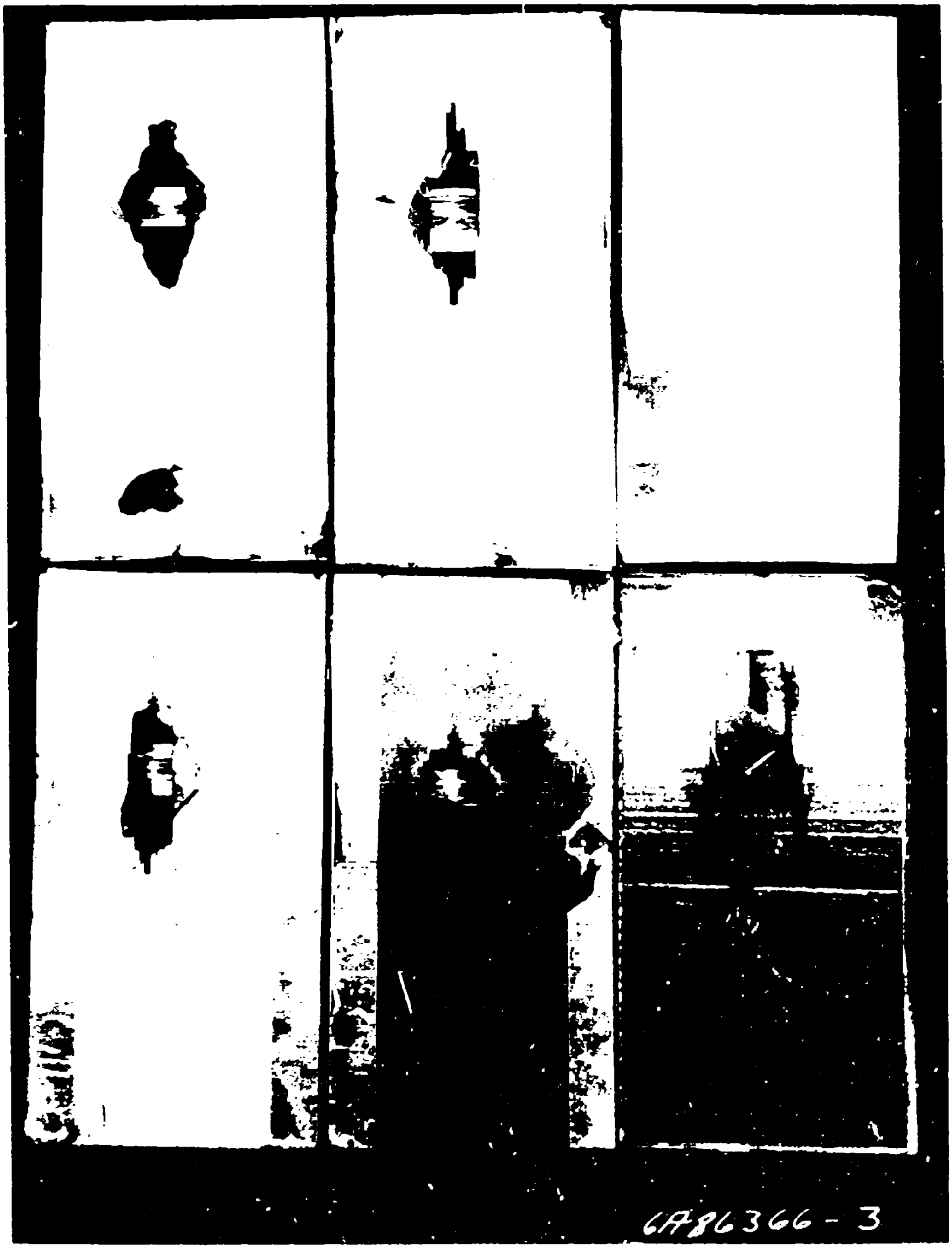


Figure A.38

174-GP60-DE10T-KF01 Figure A-38 February 27, 1970

A 10-mil EPON 1001 epoxy paint filled with potassium nitrate (KNO_3) over an undercoating of a 1-mil Kapton film was applied to this graphite panel. In addition, two aluminum diverter strips were attached to the 12-inch dimension edges. A 16.5 KV discharge was directed to this coated panel; the discharge current had a peak of 100 KA with a risetime of 20 μs and a duration of 32 μs.

No visible damage to the substrate was observed. A surface flashover pattern was shown.

175-GP61-DE10T-0000 Figure A-38 February 27, 1970

This graphite panel was coated with a 10-mil EPON 1001 epoxy paint filled with potassium nitrate (KNO_3); no undercoating was applied. Two aluminum diverter strips were attached to the 12-inch dimension edges. A 17 KV discharge was directed to this coated panel; the discharge current had a peak of 103 KA with a risetime of 15 μs and a duration of 28 μs.

The substrate was severely damaged.

176-GP62-UE05T-0000 Figure A-38 February 27, 1970

This graphite panel with no undercoating was coated with a 5-mil EPON 1001 epoxy paint filled with XC-72, a highly conductive carbon black. Two aluminum diverter strips were attached to the 12-inch dimension edges. A 17 KV discharge was directed to this coated panel; the discharge current had a peak of 98 KA with a risetime of 14 μs and a duration of 27 μs.

The substrate was severely damaged.

177-GP63-00000-ALCO Figure A-38 March 24, 1970

This aluminum honeycomb core sandwich panel had an uncoated graphite fiber reinforced plastic face sheet. The other face sheet was a glass fabric reinforced epoxy laminate. A 15 KV discharge was directed to this composite test panel. The discharge current had a peak of 106 KA with a risetime of 12 μs and a duration of 22 μs.

The graphite substrate was severely damaged; a square hole of roughly 1/2 inch dimension was punctured on the graphite substrate and honeycomb core was partially burned; however, no explosive type damage due to vaporized aluminum core was observed.

178-BR71-CW02P-0000 Figure A-39 March 24, 1970

Thin copper wires were adhesively bonded to this boron panel in a 1-inch mesh. A 16 KV discharge was directed to this panel. The discharge current had a peak of 70 KA with a risetime of 20 μs and a duration of 32 μs.

The substrate was severely damaged.

179-FG45-CW02P-0000 Figure A-39 March 24, 1970

This fiberglas panel was coated with thin copper wires in a 1-inch mesh. A 15 KV discharge was directed to this panel. The discharge current had a peak of 100 KA with a risetime of 13 μs and a duration of 23 μs.

No visible damage to this panel was observed.

180-BR72-KF01C-ALCO Figure A-39 March 24, 1970

This aluminum honeycomb core sandwich panel had an uncoated boron filament reinforced plastic face sheet. The other face sheet was a glass fabric reinforced epoxy laminate. Discharge was directed toward the boron face sheet. A 15 KV discharge was directed to this test panel; the discharge current had a peak of 100 KA with a risetime of 13 μs and a duration of 27 μs.

The boron substrate was slightly pitted and punctured with small holes, the aluminum honeycomb core was partially burned. No explosive type damage due to vaporized aluminum core was observed.

181-GP64-UE07T-KF03 Figure A-39 March 24, 1970

A composite coating system of diverter strips, a surface coating, and an undercoating was coated to this graphite panel. The undercoating was a 3-mil Kapton film and the surface coating was a 7-mil epoxy paint filled with XC-72, a highly conductive carbon black. Two aluminum diverter strips were attached to the 12-inch edges. A 15 KV discharge was directed to this coated panel. The discharge current had a peak of 104 KA with a risetime of 12 μs and a duration of 22 μs.

182-BR73-UE07T-KF03 Figure A-39 March 25, 1970

This boron panel with a 3-mil Kapton film undercoating was coated with a 7-mil epoxy paint filled with XC-72, a highly conductive carbon black. Two aluminum diverter strips were attached to the 12-inch edges. A 15 KV discharge was directed to this coated panel, the discharge had a peak of 100 KA with a risetime of 12 μs and a duration of 30 μs.

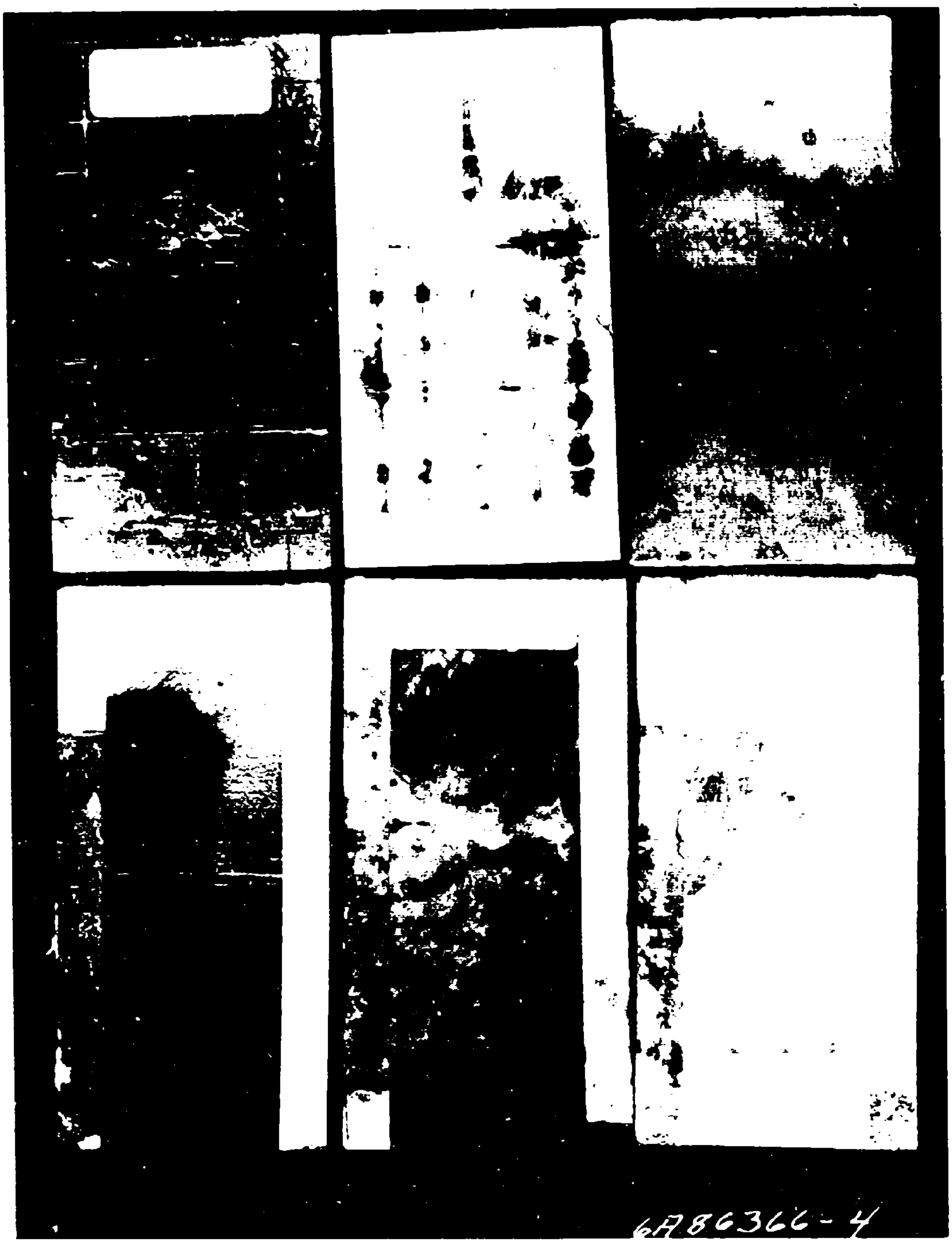


Figure A-39

No visible damage to the substrate was observed except for a crack on the left side. This crack was probably caused by the mounting frame as the shockwave pushed the test panel inward. A surface flashover pattern was shown.

183-GP65-ZE06T-KF01 Figure A-39 March 25, 1970

This graphite panel was coated with a composite coating system consisting of diverter strips, a surface coating of a 6-mil epoxy loaded with magnesium nitrate ($Mg(NO_3)_2 \cdot 6H_2O$) over an undercoating of a 1-mil Kapton film; the aluminum diverter strips were attached to the 12-inch dimension edges. A 15 KV discharge was directed to this coated panel. The discharge had a peak current of 92 KA with a risetime of 13 μs and a duration of 28 μs.

No visible damage to the substrate was observed except for a crack on the edge. This crack was probably caused by the mounting frame as the shock wave pushed the test panel inward. A surface flashover pattern was shown.

184-BR74-ZE06T-KF01 Figure A-40 March 25, 1970

This boron panel was coated with a composite coating system consisting of diverter strips, a surface coating of a 6-mil epoxy paint filled with magnesium nitrate ($Mg(NO_3)_2 \cdot 6H_2O$) over an undercoating of a 1-mil Kapton film; the two aluminum diverter strips were attached to the 12-inch dimension edges. A 15 KV discharge was directed to this coated panel. The discharge current had a peak of 100 KA with a risetime of 12 μs and a duration of 25 μs.

No visible damage to the substrate was observed; a surface flashover pattern was shown.

185-GP66-PE14T-KF01 Figure A-40 March 25, 1970

The graphite panel was coated with a 13.5-mil epoxy paint filled with potassium sulfate (K_2SO_4) over an undercoating of a 1-mil Kapton film. Two aluminum diverter strips were attached to the 12-inch dimension edges. A 15 KV discharge was directed to this coated panel; the discharge current had a peak of 112 KS with a risetime of 12 μs and a duration of 21 μs.

No damage to the substrate was observed. A surface flashover pattern was shown.

Figure A-40

186-BR75-DE10T-EP11 Figure A-40 March 25, 1970

The boron panel primarily coated with an 11-mil epoxy paint and top-coated with a 10-mil potassium nitrate (KNO_3) loaded epoxy paint. Two aluminum diverter strips were then bonded to the 12-inch dimension edges. A 15 KV discharge was directed to this coated panel; the current waveform was not recorded due to a malfunction of the oscilloscope, however, the discharge current was estimated to be 85 KA with a duration of 30 μs.

No visible damage to the substrate was observed. A surface flashover pattern was shown.

187-GP67-DE10T-EP11 Figure A-40 March 24, 1970

This graphite panel was coated with a 10-mil epoxy paint filled with potassium nitrate (KNO_3) over an underlayer of an 11-mil epoxy paint. Two aluminum diverter strips were attached to the coated panel on both edges along the 12-inch dimension. A 15 KV discharge was directed to this coated panel; the discharge current had a peak of 90 KA with a risetime of 15 μs and a duration of 30 μs.

No visible damage to the substrate was observed.

188-GP68-DE05T-KF01 Figure A-40 March 25, 1970

This graphite panel was coated with a 5-mil epoxy paint filled with potassium nitrate (KNO_3) over an undercoating of a 1-mil Kapton film. Two aluminum diverter strips were adhesively bonded to this coated panel on both edges along the 12-inch dimension. A 15 KV discharge was directed to this coated panel; the discharge current had a peak of 94 KA with a risetime of 12 μs and a duration of 26 μs.

The substrate was severely damaged.

189-BR76-DE05T-KF01 Figure A-40

This boron panel was coated with a 5-mil epoxy paint filled with potassium nitrate (KNO_3) over an undercoating of a 1-mil Kapton film. Two aluminum diverter strips were adhesively bonded to this coated panel on both edges along the 12-inch dimension. A 15 KV discharge was directed to this test panel; the discharge current had a peak of 93 KA with a risetime of 11 μs and a duration of 25 μs.

No visible damage to the substrate was observed. A definite flash-over pattern was shown.

190-BR77-DE07T-KF01 Figure A-41 March 26, 1970

This boron panel was coated with a 7-mil epoxy paint filled with potassium nitrate (KNO_3) over a 1-mil Kapton film undercoating. Two aluminum diverter strips were adhesively bonded to this coated panel on both edges along the 12-inch dimension. No discharge can be initiated to

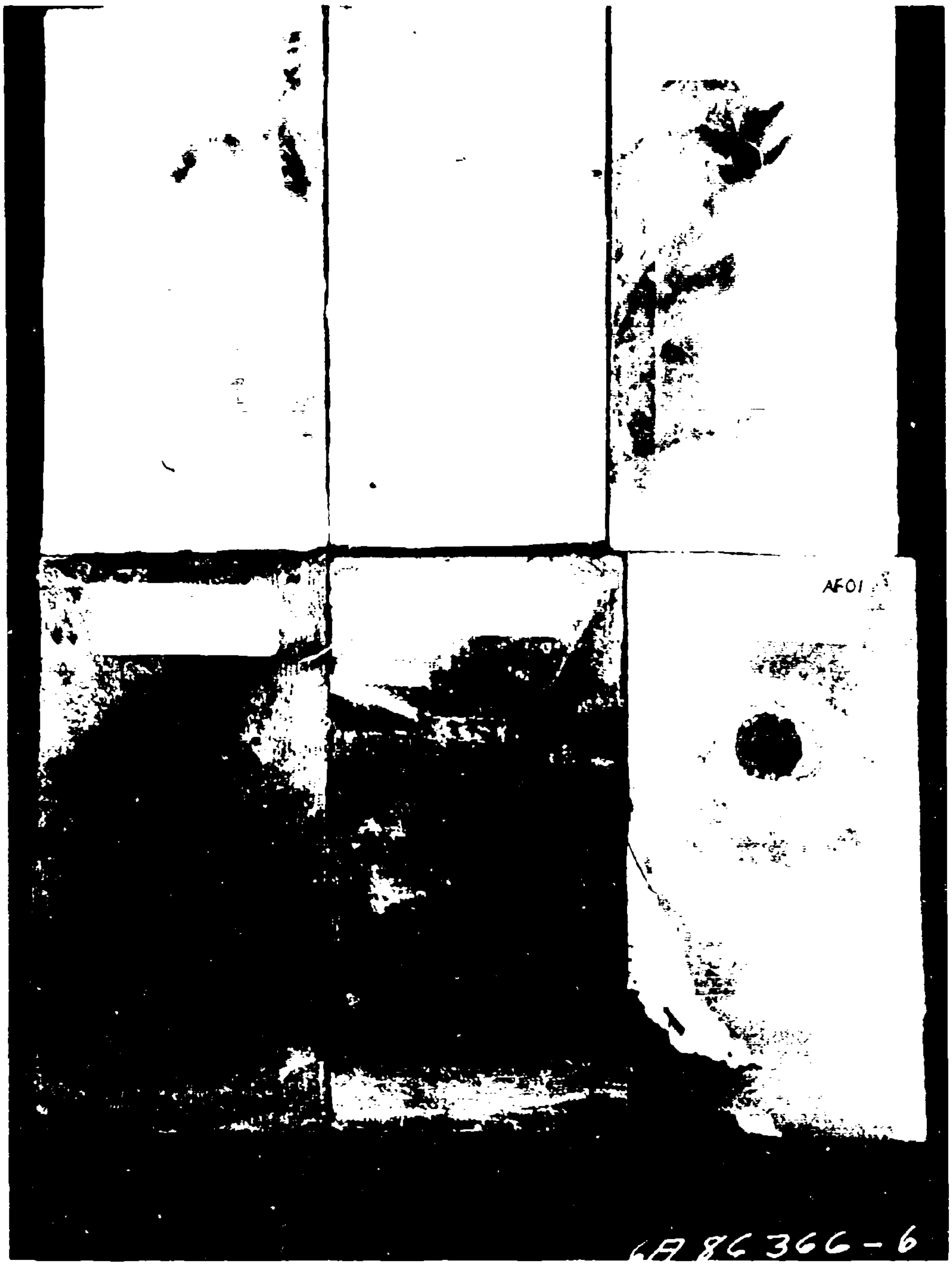


Figure A 41

to this test sample at 20 KV for a 3/16-inch gap; however, a discharge was directed at 18 KV with a gap of 1/16 inch. The discharge had a peak current of 108 KA with a risetime of 11 μs and a duration of 29 μs.

No visible damage to the substrate was observed. A flashover pattern and a track of a burned paint were shown.

191-GP69-DE071-KF01 Figure A-41 March 26, 1970

This graphite panel was coated with a 7-mil epoxy paint filled with potassium nitrate (KNO_3) over a 1-mil Kapton film undercoating. Two aluminum diverter strips were attached to both edges along the 12-inch dimension. No discharge can be initiated at 20 KV and a 3/16 inch gap; however, a discharge of 105 KA with a risetime of 12 μs and a duration of 23 μs was directed to this test sample at 15 KV with a gap of 1/16 inch.

No visible damage to the substrate was observed. A burned track of paint was shown.

192-BR78-PE141-KF01 Figure A-41 March 26, 1970

This boron panel was coated with a 13.5-mil epoxy paint filled with potassium sulfate (K_2SO_4) over a 1-mil Kapton film undercoating. Two aluminum diverter strips were adhesively bonded to both edges along the 12-inch dimension. A 15 KV discharge was directed to this coated panel; the discharge current had a peak of 98 KA with a risetime of 12 μs and a duration of 26 μs.

No visible damage to the substrate was observed. A burned off strip of coating was shown.

193-GP70-SW08P-0000 Figure A-41 April 10, 1970

This graphite panel was coated with knitted wire fabric which had a 3.5-mil diameter silver plated brass wire. No underlayer was applied. Two 15 KV discharges were directed to this coated panel; the discharge current had a peak of 90 KA with a risetime of 11 μs and a duration of 25 μs.

The wire fabric was peeled off the substrate in both cases, and the front surface of the substrate was charred and partially delaminated.

194-BR79-SW08P-0000 Figure A-41 April 10, 1970

This boron panel was coated with knitted wire fabric which had a 3.5-mil diameter silver plated brass wire. No underlayer was applied. A 16 KV discharge was directed to this coated panel; the discharge was not recorded due to the early triggered oscilloscope; however, it was estimated to be a 100 KA with a duration of 25 μs.

The fabric was largely vaporized and a few small burned marks were observed on the substrate.

195-BR80-VA05C-AF01 · Figure A-41 April 10, 1970
A 1-mil aluminum foil topcoated with a 5-mil Dynacryl acrylic paint was applied to this boron panel. A 15 KV discharge was directed to this coated panel; the discharge had a peak of 108 KA with a duration of 20 μs.

A crack on the substrate was observed.

196-GP71-VA05C-AF01 · Figure A-42 April 10, 1970
A 1-mil aluminum foil topcoated with a 5-mil Dynacryl acrylic paint was applied to this graphite panel. A 15 KV discharge was directed to this coated panel; the discharge had a peak current of 106 KA with a duration of 20 μs.

The front surface of the substrate was slightly burned.

197-GP72-DE08T-KF01 Figure A-42 April 10, 1970
This graphite panel was first coated with a 1-mil Kapton film and two aluminum diverter strips were bonded to both edges along the 12-inch dimension. An 8 mil epoxy paint filled with potassium nitrate (KNO_3) then topcoated this panel. A 15 KV discharge was directed to this coated panel; the discharge current had a peak of 110 KA with a duration of 20 μs.

No visible damage to the substrate was observed except for a slightly burned surface on the left side.

198-GP73-DE11T-EP05 Figure A-42 April 13, 1970
This graphite panel was coated with a 11.2-mil potassium nitrate (KNO_3) filled epoxy paint over an undercoating of a 4.8-mil clear epoxy paint. Two Aluminum diverter strips were attached to both edges along the 12-inch dimension. A 15 KV discharge was directed to this coated panel; the discharge had a peak current of 94 KA with a risetime of 12 μs and a duration of 24 μs.

The substrate was severely damaged.

199-BR81-DE08T-KF01 Figure A-42 April 13, 1970
This boron panel was coated with an 8-mil potassium nitrate (KNO_3) filled epoxy paint over a 1-mil Kapton film undercoating. Two aluminum diverter strips were bonded to the 12-inch dimension edges. A 25 KV discharge was directed to this coated panel; the discharge had a peak current of 180 KA with a risetime of 12 μs and a duration of 22 μs.

No visible damage to the substrate was observed.

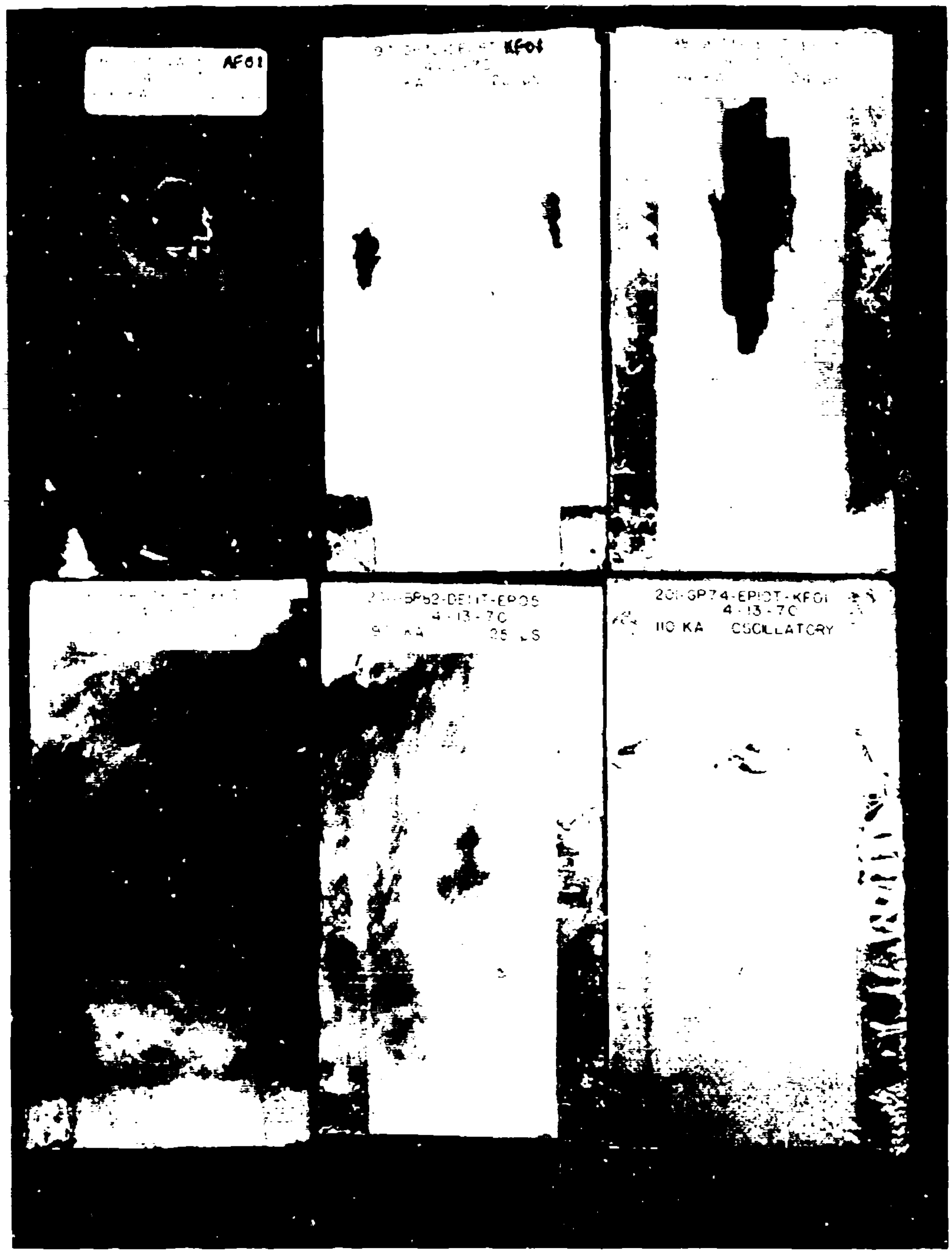


Figure A-42

200-BR82-DE11T-EF05 Figure A-42 April 13, 1970

This boron panel was coated with a 11.2-mil potassium nitrate (KNO_3) filled epoxy paint over an undercoating of a 4.8-mil clear epoxy paint. Two aluminum strips were bonded to the 12-inch dimension edges. A 15 KV discharge was directed to this coated panel; the discharge current was not recorded, however, it was estimated to be a 90 KA with a duration of 25 μs.

No visible damage to the substrate was observed. A flashover pattern was shown.

201-GP74-EP10T-KF01 Figure A-42 April 13, 1970

This graphite panel was coated with a 10-mil EPON 1001 epoxy paint over a 1-mil Kapton film undercoating. Two aluminum strips were bonded to the 12-inch dimension edges. A 15 KV discharge with the crowbar switch disconnected was directed to this coated panel; the current had a peak of 110 KA with a ring frequency of 40 kHz.

No visible damage to the substrate was observed. A flashover pattern was shown.

202-BR83-EP10T-KF01 Figure A-43 April 13, 1970

This boron panel was coated with a 10-mil EPON 1001 epoxy paint over a 1-mil Kapton film undercoating. Two aluminum strips were attached to the 12-inch dimension edges. A 15 KV discharge was directed to this coated panel; the discharge had a peak current of 94 KA with a risetime of 11 μs and a duration of 24 μs.

No visible damage to the substrate was observed. A flashover pattern was shown.

203-FG46-DE10C-0000
204-FG47-DE10C-BN06
205-FG48-DE10T-0000
205-FG49-DE10T-BN06

These four fiberglas panels were coated with different coatings and no discharge could be initiated to these panels at a voltage of 21 KV and a gap of 1/16 inch.

The coatings used were:

1. A 10-mil potassium nitrate (KNO_3) filled epoxy paint for Panel No. 203.

2. A 10-mil potassium nitrate filled epoxy paint over an undercoating of a 6-mil boron nitride (BN) filled epoxy paint for Panel No. 204.

3. A 10-mil potassium nitrate filled epoxy paint bonded with two aluminum strips along the 12-inch dimension edges for Panel No. 205.

4. The same coating system as the above one plus an undercoating of a 6-mil boron nitride filled epoxy paint for Panel No. 206.

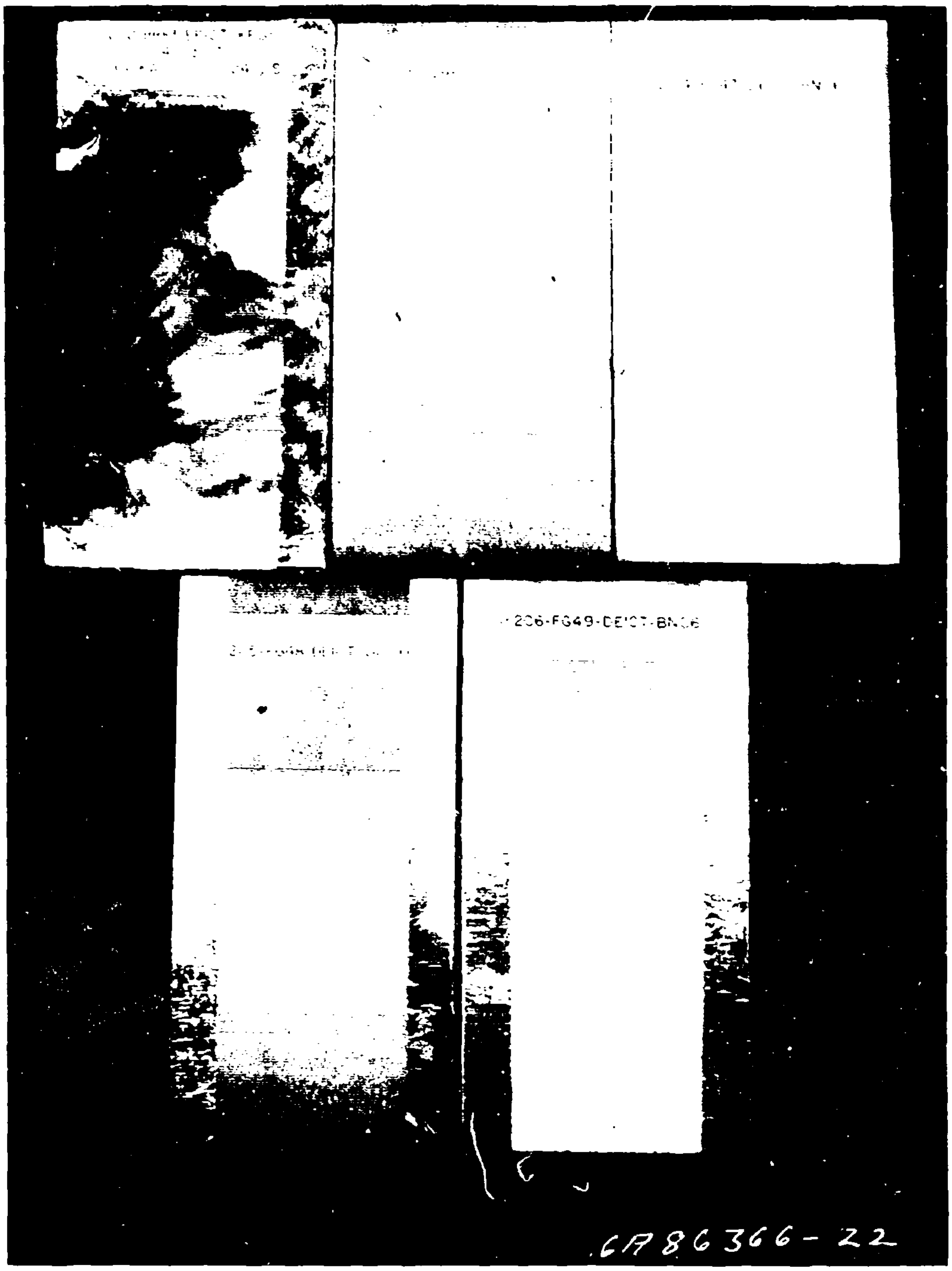


Figure A-43

207-GP75-AD08E-0000 Figure A-44 May 18, 1970

This graphite panel was coated with aluminum knitted wire mesh having a wire diameter of 4 mils and a mesh density of 13 x 24 per inch. The mesh was applied to one entire surface of the substrate and impregnated with an epoxy resin, BMS 5-29; no undercoating was applied. A 17 KV discharge was directed to this coated panel, the discharge had a peak current of 90 KA with a duration of 22 μs and a risetime of 10 μs.

The front few layers of the graphite substrate were locally burned; however, no puncture was observed.

208-GP76-AD16B-KF01 Figure A-44 May 18, 1970

This graphite panel was coated with aluminum knitted wire mesh over a 1-mil Kapton film undercoating. The mesh, having a wire diameter of 8 mils and a mesh density of 5 x 9 per inch, was bonded to the Kapton film with an epoxy resin, BMS 5-29. A 19 KV discharge was directed to this coated panel; the discharge had a peak current of 103 KA with a risetime of 10 μs and a duration of 21 μs.

The front few layers of the substrate were badly burned, and a surface flashover was also shown.

209-BR84-AD08E-KF01 Figure A-44 May 18, 1970

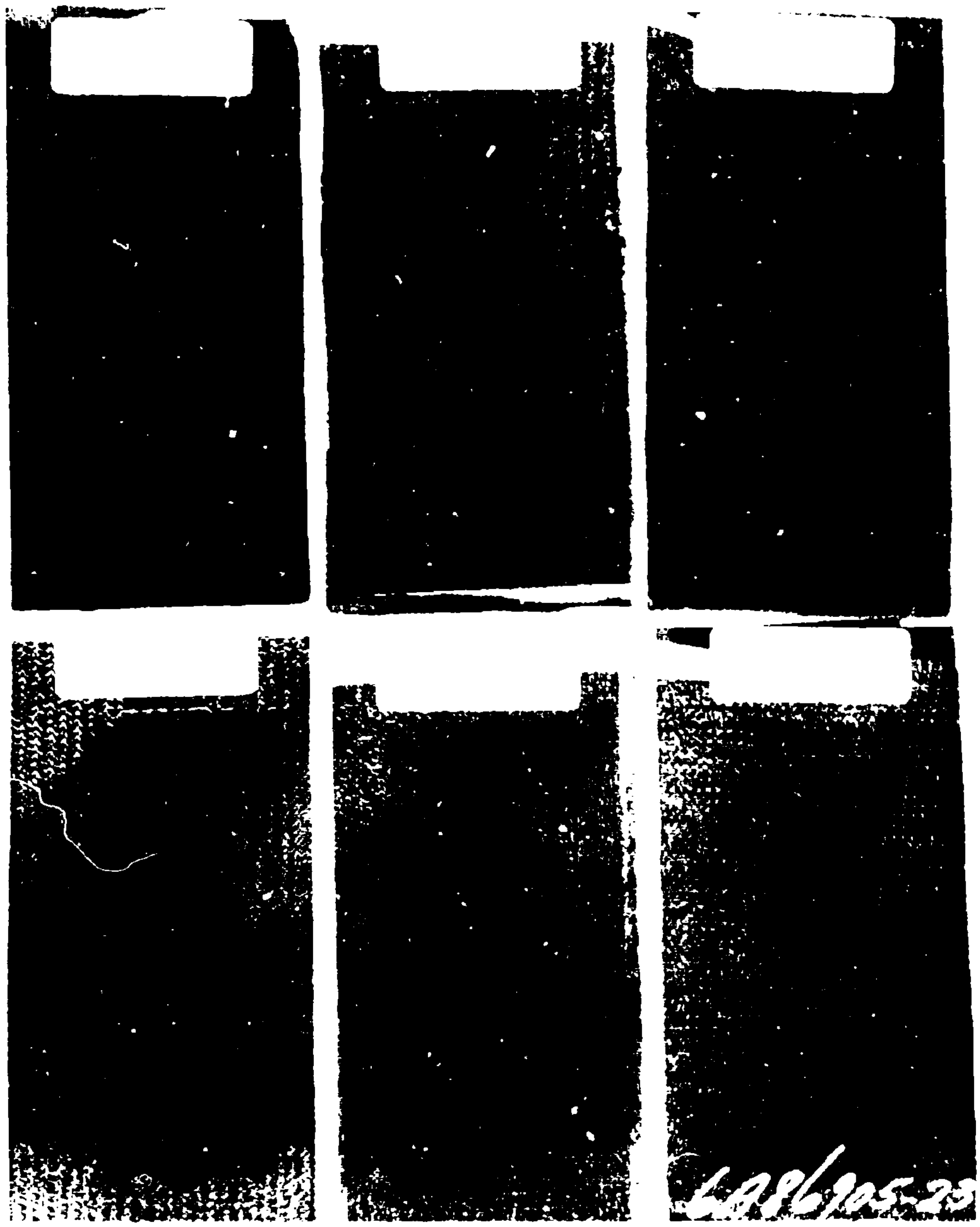
This boron panel was coated with aluminum knitted wire mesh over a 1-mil Kapton film undercoating. The mesh, having a wire diameter of 4 mils and mesh density of 13 x 24 per inch, was bonded to the Kapton film with an epoxy, BMS 5-29. A 19 KV discharge was directed to this coated panel; the discharge had a peak current of 90 KA with a risetime of 12 μs and a duration of 23 μs.

No visible damage to the substrate was observed; a surface flashover pattern was shown.

210-BR85-AD16B-0000 Figure A-44 May 18, 1970

This boron panel was coated with aluminum knitted wire mesh, having a wire diameter of 8 mils and a mesh density of 5 x 9 per inch. The wire mesh was bonded to the substrate with an epoxy, BMS 5-29; no undercoating was applied. A 20 KV discharge was directed to this coated panel; the discharge had a peak current of 103 KA with a risetime of 10 μs and a duration of 22 μs.

No visible damage to the substrate was observed. A surface flashover pattern was shown.



211-BR86-AD12A-0000 Figure A-44 May 18, 1970

This boron panel was coated with aluminum knitted wire mesh having a wire diameter of 6 mils and a mesh density of 6 x 11. The wire mesh wa bonded to the substrate with an epoxy, BMS 5-29; no undercoating was applied. A 20 KV discharge was directed to this coated panel; the discharge had a peak current of 106 KA with a risetime of 11 μs and a duration of 22 μs.

No visible damage to the substrate was observed. A surface flashover pattern was shown.

212-GP77-AD20B-KF01 Figure A-44 May 18, 1970

This graphite panel was coated with aluminum knitted wire mesh over a 1-mil Kapton film undercoating. The wire mesh, having a wire diameter of 10 mils and mesh density of 5 x 9 per inch, was bonded to the Kapton film with an epoxy resin, BMS 5-29. A 20 KV discharge was directed to this coated panel; the discharge had a peak current of 106 KA with a risetime of 10 μs and a duration of 21 μs.

The front few layers of substrate were locally burned.

213-BR87-AD20B-0000 Figure A-45 May 19, 1970

This boron panel was coated with aluminum knitted wire mesh having a wire diameter of 10 mils and a mesh density of 5 x 9 per inch. The wire mesh was bonded to the substrate with BMS 5-29 epoxy, and no undercoating was applied.

A 20 KV discharge was directed to this coated panel, the discharge had a peak current of 100 KA with a risetime of 11 μs and a duration of 22 μs. No visible damage to the substrate was observed, a surface flashover was however shown.

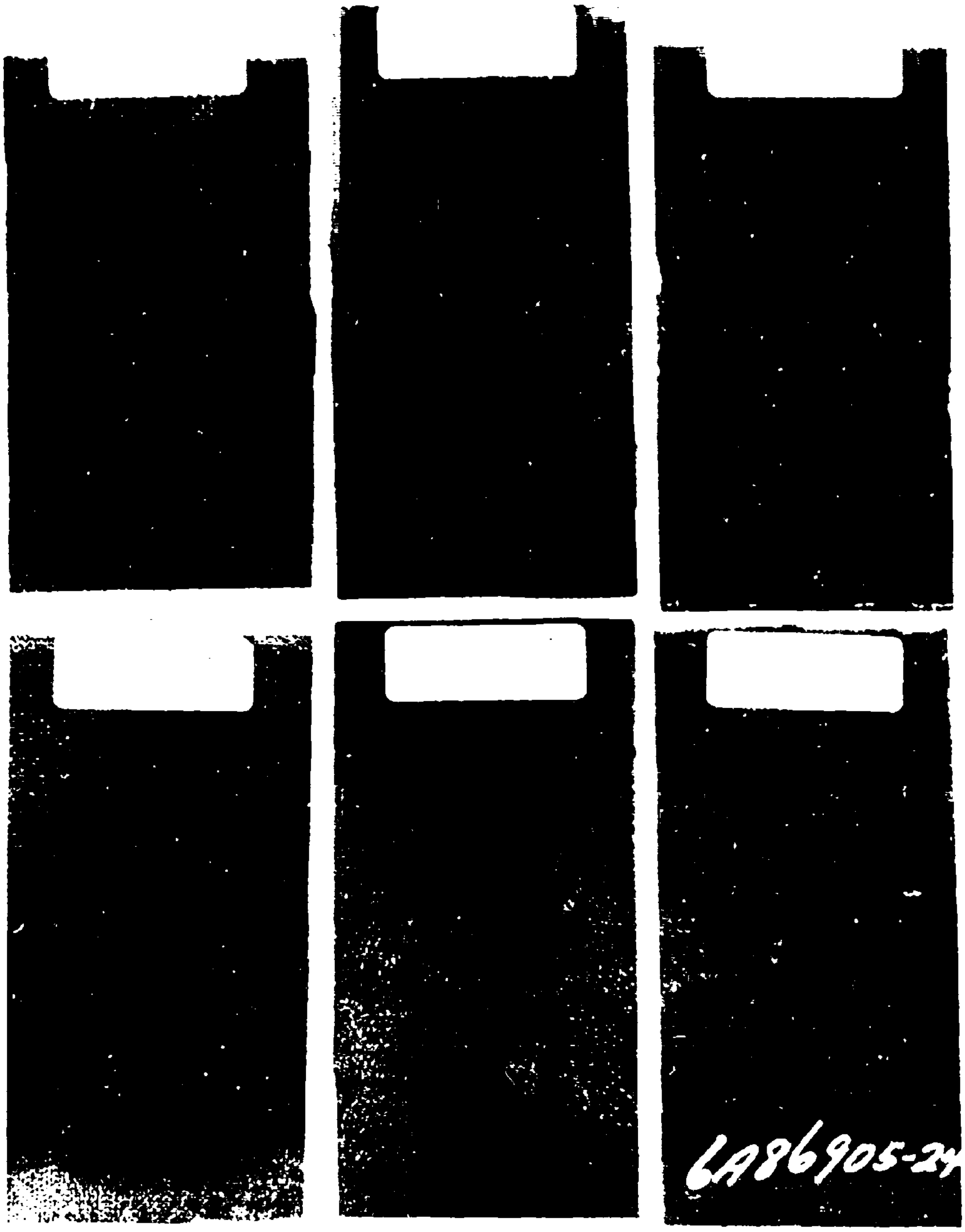
214-GP78-AD12A-KF01 Figure A-45 May 19, 1970

This graphite panel was coated with aluminum knitted wire mesh over a 1-mil Kapton film undercoating. The wire mesh having a wire diameter of 6 mils and a mesh density of 6 x 11 was bonded to the Kapton film with BMS 5-29 epoxy.

An 18.5 KV discharge was directed to this coated panel, the discharge had a peak current of 98 KA with a risetime of 10 μs and a duration of 21 μs. The front surface of the substrate was burned.

215-GP79-AD12F-KF01 Figure A-45 May 19, 1970

This graphite panel was coated with aluminum knitted wire mesh over a 1-mil Kapton film undercoating. The wire mesh having a wire diameter of 6 mils and a mesh density of 8 x 14 per inch was bonded to the Kapton film with BMS 5-29 epoxy.


6A86905-24

A 19 KV discharge was directed to this coated panel, the discharge had a peak current of 110 KA with a risetime of 10 μs and a duration of 20 μs.

The front surface of the substrate was pitted and slightly burned.

216-BR88-AD12F-0000 Figure A-45 May 19, 1970
This boron panel was coated with aluminum knitted wire mesh having a wire diameter of 6 mils and a mesh density of 8 x 14 per inch. The wire mesh was bonded to the substrate with BMS 5-29 epoxy, and no undercoating was applied.

A 20 KV discharge was directed to this coated panel, the discharge had a peak current of 110 KA with a risetime of 11 μs and a duration of 21 μs.

No visible damage to the substrate was observed, a surface flashover was shown.

217-BR89-AM04H-0000 Figure A-45 June 10, 1970
This boron panel was coated with knitted Monel wire fabric which had a wire diameter of 2 mils and a mesh density of 22 x 40 per inch. The wire fabric was bonded to the substrate with BMS 5-29 adhesive; no undercoating was applied.

An 18 KV discharge was directed to this panel, the discharge had a peak current of 88 KA with a risetime of 11 μs and a duration of 20 μs.

No visible damage to the substrate was observed except for a small burned mark.

218-BR90-AD08E-0000 Figure A-45 June 10, 1970
This boron panel was coated with aluminum knitted wire fabric having a wire diameter of 4 mils and a mesh density of 13 x 24 per inch. The mesh was split at the center so that the discharge current was forced to either arc over the gap or breakdown the boron sheath. The fabric was bonded to the substrate with BMS 5-29 adhesive; no undercoating was applied.

An 18 KV discharge was directed to this coated panel, the current had a peak of 65 KA with a risetime of 13 μs and a duration of 26 μs.

No visible damage to the substrate was observed, a surface flashover pattern was shown.

219-GP80-AD08B-EP10 Figure A-46 June 16, 1970

This graphite panel was coated with aluminum knitted wire mesh over a 10-mil epoxy undercoating. The wire mesh had a wire diameter of 4 mils and a mesh density of 5 x 9 per inch and was integrally bonded to the substrate.

A 17 KV discharge was directed to this coated panel, the discharge had a peak current of 82 KA with a risetime of 11 μs and a duration of 25 μs. The substrate was damaged as a hole was punctured.

220-BR91-AD08B-0000 Figure A-46 June 16, 1970

This boron panel was coated with aluminum knitted wire fabric with a mesh density of 5 x 9 per inch and a wire diameter of 4 mils. The mesh was bonded to the substrate with BMS 5-29 adhesive; no undercoating was applied.

Two 18 KV discharges were initiated to this test panel. The first discharge had a peak current of 85 KA with a risetime of 13 μs and a duration of 25 μs. No visible damage to the substrate was observed; however, it was found from the next shot that the integrity of the surface coating was impaired.

The second shot had a peak current of 65 KA with a risetime of 16 μs and a duration of 40 μs. The front surface of the substrate was slightly burned and a surface flashover was shown; however no puncture was observed.

221-GP81-AD08G-EP10 Figure A-46 June 16, 1970

This graphite panel was coated with aluminum knitted wire mesh which had a wire diameter of 4 mils and a mesh density of 10 x 18 per inch. The mesh was integrally bonded to the 10 mil epoxy undercoating.

A 19 KV discharge was directed to this coated panel, the discharge had a peak current of 100 KA with a risetime of 11 μs and a duration of 23 μs. The substrate was damaged and punctured with some small holes.

222-BR92-AD08G-0000 Figure A-46 June 16, 1970

This boron panel was coated with aluminum knitted wire mesh having a mesh density of 10 x 18 per inch and a wire diameter of 4 mils. The mesh was bonded to the substrate with BMS 5-29 epoxy; no undercoating was applied.

A 19 KV discharge was directed to this coated panel, the discharge had a peak current of 95 KA with a risetime of 11 μs and a duration of 23 μs. No visible damage to the substrate was observed.

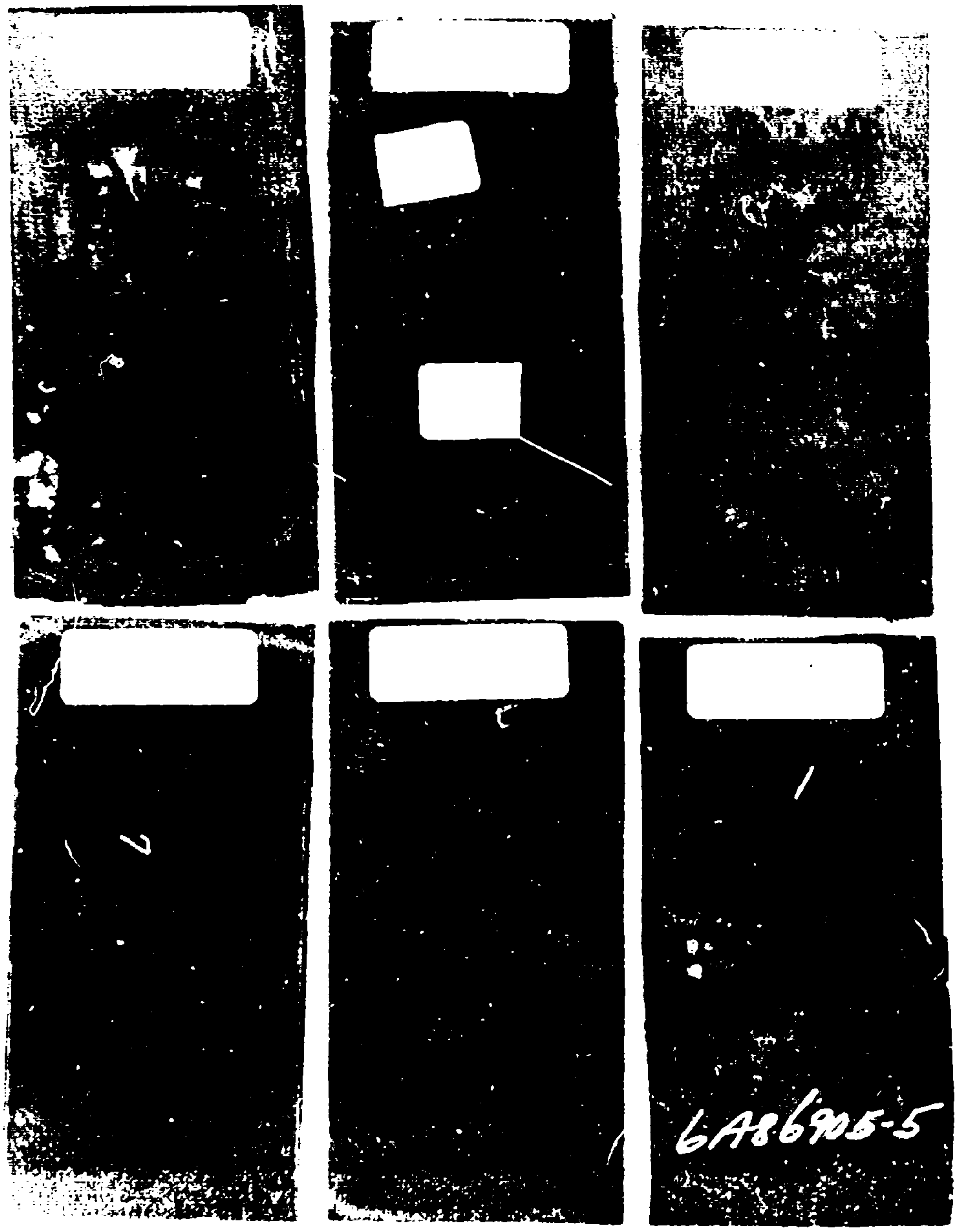


Figure B-48

223-BR93-AD08F-0000 Figure A-46 June 16, 1970

This boron panel was coated with aluminum knitted wire fabric having a wire diameter of 4 mils and a mesh density of 8 x 14 per inch. The mesh was bonded to the substrate with BMS 5-29; no undercoating was applied.

A 19 KV discharge was directed to this coated panel, the current had a peak of 98 KA with a risetime of 11 μs and a duration fo 22 μs. No visible damage to the substrate was observed.

224-GP82-AD08F-0000 Figure A-46 June 16, 1970

This graphite panel was coated with aluminum knitted wire fabric having a wire diameter of 4 mils and a mesh density of 8 x 14 inch. The mesh was bonded to the substrated with BMS 5-29 epoxy; no undercoating was applied.

A 19 KV discharge was initiated to this coated panel, the discharge had a peak current of 100 KA with a risetime of 11 μs and a duration of 22 μs. The front surface of the substrate was charred. The coating was peeled off the substrate; however, no puncture was observed.

225-BR94-AR16W-0000 Figure A-47 June 17, 1970

This boron panel was coated with aluminum woven wire fabric having a wire diameter of 8 mils and a mesh density of 60 x 60 per inch. The fabric was applied to the substrate with BMS 5-29 epoxy; no undercoating was applied.

Two 2-component lightning discharges consisting of a high current component and a high coulomb component were directed to this coated panel. The first high current component was an 18 KV discharge to yield a peak current of 100 KA and was immediately followed by a second high coulomb component which had 150 amp for 1 second and 240 amp for 1.5 second respectively.

The aluminum fabric surface coating was largely vaporized and the front surface of the substrate was badly burned; however, no puncture was observed even a discoloration hot spot ring was formed.

226-GP83-AR04Z-0000 Figure A-47 June 17, 1970

This graphite panel was coated with aluminum woven wire fabric having a wire diameter of 2.1 mils and a mesh density of 200 x 200 per inch. The mesh was bonded to the substrate with BMS 5-29 epoxy; no undercoating was applied.

Two two-component lightning strokes were initiated to this coated panel. The first component was an 18 KV discharge and was immediately followed by a second high coulomb component which was only 15 coulombs at a 150 amp for 100 μs, The arc was extinguished by itself due to the high impedance of the coating.

No severe damage was observed to the substrate as a result of tests.

Figure A-47

227-GP84-AD08E-KF03 Figure A-47 June 17, 1970

This graphite panel was coated with aluminum knitted wire mesh over a 3-mil Kapton film undercoating. The mesh with a wire diameter of 4 mils and a mesh density of 13 x 24 was bonded to the substrate with BMS 5-29 epoxy. An 18 KV oscillatory discharge was directed to this coated panel. The discharge was failed to be recorded due to the malfunction of the oscilloscope. However, it was estimated to be 100 KA.

No visible damage to the neighboring area of the attachement was observed; however, the arc was flashed over the surface and reattached to the edges of graphite fibers.

228-BR95-AF03P-0000 Figure A-47 June 23, 1970

This boron panel was partially coated with 1-inch wide, 3-mil thick aluminum tapes. Three tapes were along the 12-inch dimension side on both edges and the center of the panel; two tapes were along the 6-inch dimension side on the ends.

A 27 KV discharge was directed to this test panel, the discharge had a peak current of 170 KA with a risetime of 10 μs and a duration of 19 μs. The aluminum tapes were almost completely vaporized and a very smoky surface was shown; however, no visible damage to the substrate was observed.

229-GP85-AF03P-0000 Figure A-47 June 23, 1970

This graphite panel was coated with 1-inch wide, 3-mil thick aluminum tapes. Three tapes were along the 12-inch dimension side on both edges and the center; two tapes were along the 6-inch dimension on both ends.

A 27 KV discharge was initiated to this coated panel, the discharge had a peak current of 170 KA with a risetime of 10 μs and a duration of 19 μs. The aluminum tapes were almost completely vaporized and the front surface of the substrate was partially charred; however, no puncture was shown.

230-GP86-CR04Z-0000 Figure A-47 June 23, 1970

This graphite panel was coated with bronze woven wire fabric having a wire diameter of 2.1 mils and a mesh density of 200 x 200 per inch. The wire fabric was bonded to the substrate with BMS 5-29 epoxy and the wire was well embedded in the adhesive.

A 27 KV discharge was directed to this coated panel, the discharge had a peak current of 154 KA with a risetime of 10 μs and a duration of 19 μs. The surface coatings was mostly vaporized and a small area of charred surface was also shown; however, no puncture was shown.

231-BR96-CR04C-0000 Figure A-48 June 23, 1970

This boron panel was coated with bronze woven wire fabric having a wire diameter of 2.1 mils and mesh density of 200 x 200 per inch. The wire fabric was bonded to the substrate with BMS 5-29 epoxy and embedded well in the adhesive; no undercoating was applied.

A 30 KV discharge was directed to this coated panel. The discharge had a peak current of 170 KA with a risetime of 10 μs and a duration of 20 μs. No visible damage to the substrate was observed. A surface flashover was shown.

232-BR97-AD08G-0000 Figure A-48 June 23, 1970

This boron panel was coated with aluminum knitted wire fabric having a wire diameter of 4 mils and a mesh density of 10 x 18. The wire mesh was bonded to the substrate with BMS 5-29 epoxy; no undercoating was applied.

A 30 KV discharge was directed to this coated panel, the discharge had a peak current of 176 KA with a risetime of 10 μs and a duration of 19 μs. A very small hole was punctured and some minor damage was observed. A surface flashover was also shown.

233-BR98-AR08X-0000 Figure A-48 June 23, 1970

This boron panel was coated with aluminum woven wire fabric having a wire diameter of 4 mils and a mesh density of 120 x 120 per inch. The wire fabric was bonded to the substrate with BMS 5-29 epoxy; no undercoating was applied.

A 30 KV discharge was applied to this coated panel. The discharge had a peak current of 200 KA with a risetime of 10 μs and a duration of 40 μs. No visible damage was observed.

234-GP87-AR08X-0000 Figure A-48 June 23, 1970

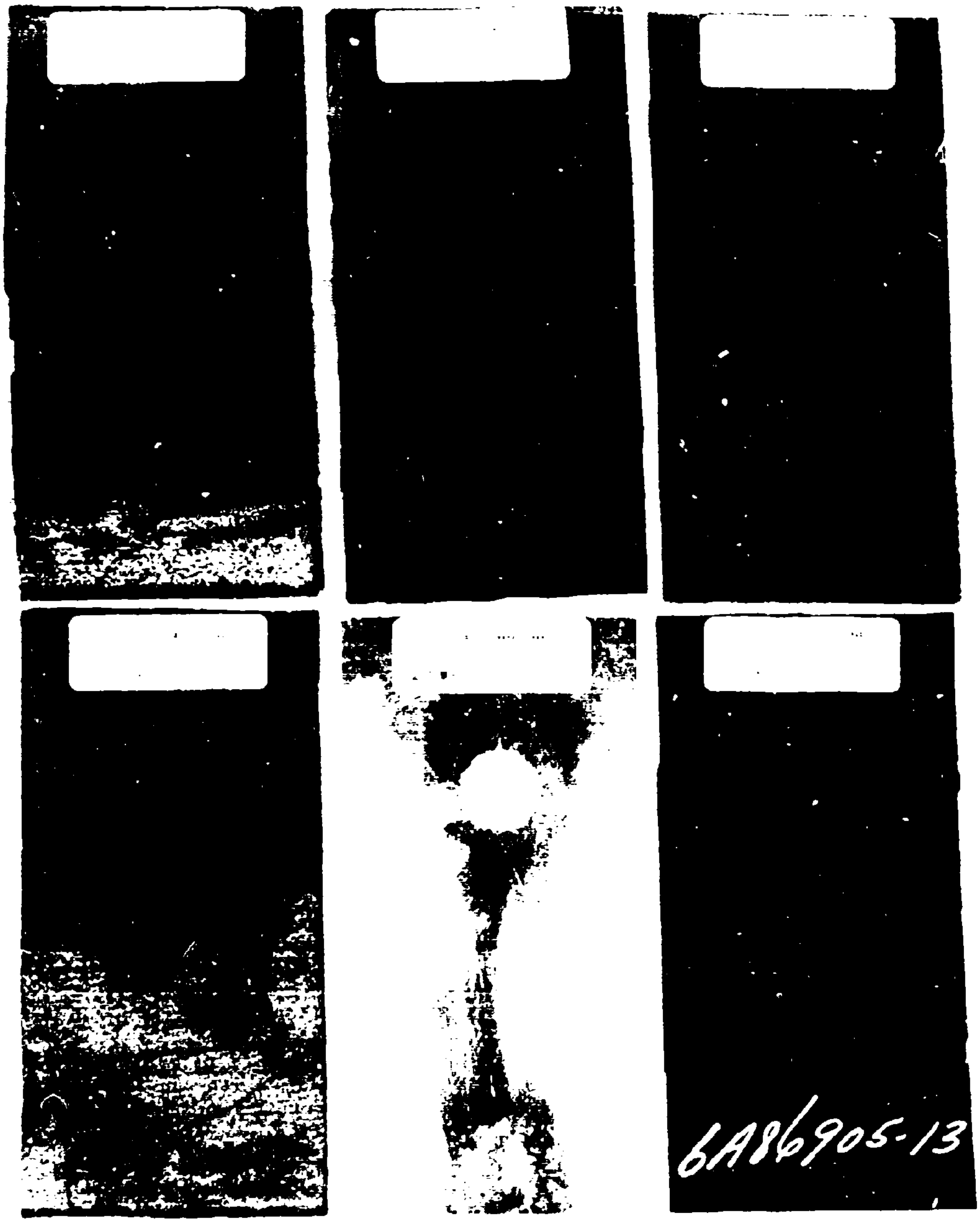
This graphite panel was coated with aluminum woven wire fabric having a wire diameter of 4 mils and a mesh density of 120 x 120 per inch. The wire fabric was bonded to the substrate with BMS5-29 epoxy; no undercoating was applied.

A 27 KV discharge was directed to this coated panel, the discharge had a peak current of 178 KA with a risetime of 10 μs and a duration of 18 μs.

No visible damage was observed.

235-AL01-00000-0000 Figure A-48 July 23, 1970

This is a 2024-T3 aluminum panel with a thickness of 40 mils. A 28 KV discharge was directed to this control sample and the discharge current had a peak current of 215 KA with a risetime of 14 μs and a duration of 30 μs.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236-BR99-AD08G-0000 Figure A-48 July 23, 1970
This boron panel was coated with aluminum knitted wire mesh having a wire diameter of 4 mils and a mesh density of 10 x 18 per inch. The mesh was bonded to the substrate with BMS 5-29 epoxy; no undercoating was applied.

A 28 KV discharge was directed to this coated panel, the discharge current had a peak current of 150 KA with a risetime of 11 μs and a duration of 23 μs. The substrate was punctured with a small hole. A surface flashover was also shown.

237-GP88-AD08G-0000 Figure A-49 July 23, 1970
This graphite panel was coated with aluminum knitted wire fabric having a wire diameter of 4 mils and a mesh density of 10 x 18. The wire mesh was integrally bonded substrate; no undercoating was applied.

A 30 KV discharge was directed to this coated panel, the discharge current had a peak of 170 KA with a risetime of 11 μs and a duration of 23 μs. The front surface of the substrate was severely burned and a surface flashover was also shown; however, no puncture was observed.

238-BR00-AM04H-0000 Figure A-49 July 23, 1970
This boron panel was coated with knitted woven wire fabric having a wire diameter of 2 mils and a mesh density of 22 x 40. The wire mesh was bonded to the substrate with BMS 5-29 epoxy, no undercoating was applied.

A 30 KV discharge was directed to this coated panel, the discharge had a peak current of 165 KA with a duration of 24 μs and a risetime of 14 μs. A small hole was punctured.

239-AL02-00000-0000 Figure A-49 July 24, 1970
This is a 2024-T3 aluminum panel with a thickness of 40 mils. A two-component lightning stroke was directed to this panel. The first high current component was a 100 KA crest and the follow-on second component was 175 amp for 1.5 seconds to yield a total 263 coulombs.

A hole of approximately 1-inch diameter was observed.

240-GP89-AD08X-0000 Figure A-49 July 24, 1970
This graphite panel was coated with aluminum knitted wire fabric having a wire diameter of 4 mils and a mesh density of 120 x 120 per inch. The wire fabric was integrally bonded to the substrate and no undercoating was applied.

Two discharges were directed to this coated panel. The first one was 175 amp for 400 μs, and the second one was 267 amp for 1.5 seconds which yielded a total 400 coulombs. A hole was burned through the graphite substrate by the second discharge.

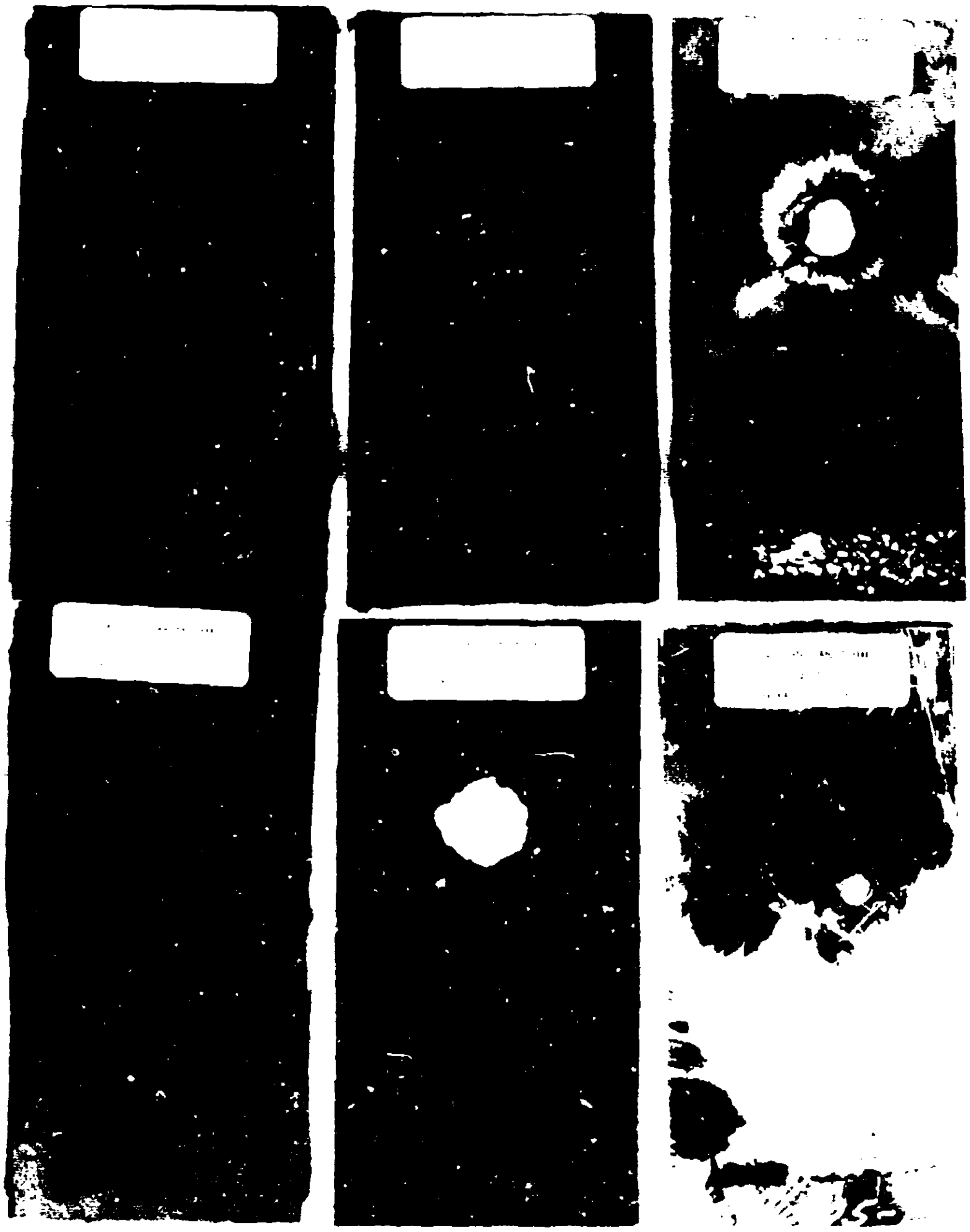


Figure A-39

241-BR01-AD08X-0000 Figure A-49 July 24, 1970

This boron panel was coated with knitted aluminum wire fabric having a wire diameter of 4 mils and a mesh density of 120 x 120 per inch. The fabric was integrally bonded to the substrate.

A 500 coulomb (285 amp for 1.75 seconds) discharge was directed to this coated panel. A 1.5-inch diameter hole was observed.

242-GP90-AF01/2C-0000 Figure A-49 July 24, 1970

A one-half-mil aluminum foil was integrally bonded to this graphite panel with no undercoating applied.

A 16 KV discharge was directed to this coated panel, the discharge had a peak current of 100 KA with a risetime of 10 μs and a duration of 18 μs. The substrate was damaged.

243-BR02-AF01/2C-0000 Figure A-50 July 24, 1970

This boron panel was integrally bonded with a one-half-mil aluminum foil. No undercoating was applied. A 16 KV discharge was directed to this coated panel, the current had a peak current of 100 KA with a risetime of 10 μs and a duration 18 μs.

The substrate was slightly damaged within a very small area as opposite to the discharge probe.

244-GP91-FE03Y-0000 Figure A-50 July 24, 1970

This graphite panel was integrally bonded with stainless steel woven wire fabric which had a wire diameter of 1.4-mil and a mesh density of 325 x 325 per inch. No undercoating was applied.

A 20 KV discharge was directed to this coated panel, the current had a peak current of 100 KA with a risetime of 10 μs and a duration of 20 μs.

The substrate was severely burned.

245-BR03-FE03Y-0000 Figure A-50 July 24, 1970

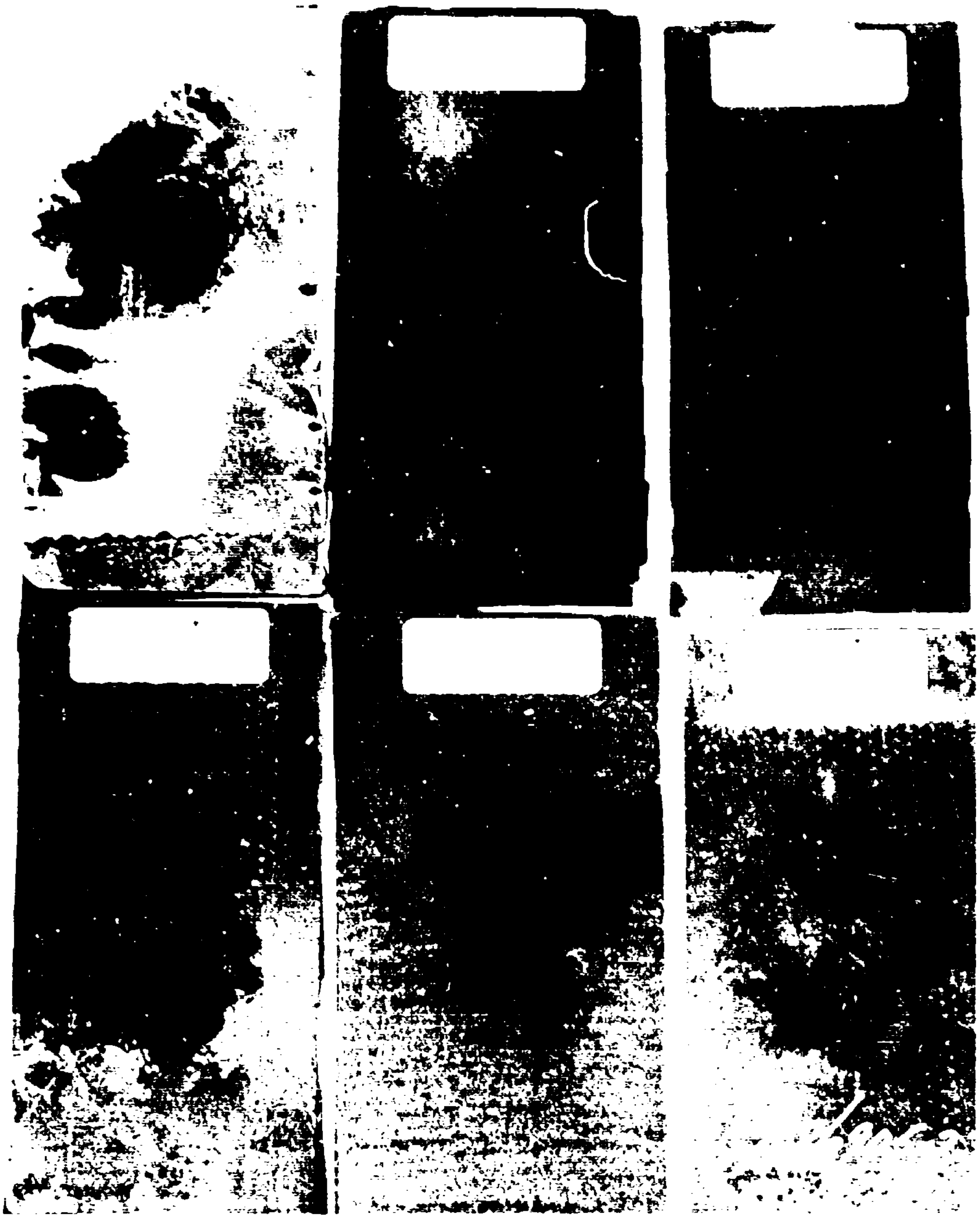
This boron panel was coated with stainless steel woven wire fabric. The fabric with a wire diameter of 1.4 mils and a mesh density of 325 x 325 per inch was integrally bonded to the substrate; no undercoating was applied.

A 20 KV discharge was directed to this coated panel, the current had a peak of 90 KA with a risetime of 10 μs and a duration of 24 μs.

The substrate was slightly damaged.

246-GP92-CR07X-0000 Figure A-50 August 17, 1970

This graphite panel was coated with bronze woven wire fabric which had a wire diameter of 3.5 mils and a mesh density of 120 x 120 per inch. The wire fabric was bonded to the substrate with BMS5-29 adhesive, and no undercoating was applied.



Two 2-component lightning strokes with the first high current component of approximately 100 KA were initiated to this coated panel. The first discharge had a second high coulomb component of 213 coulomb at a DC of 125 amp for 1.7 seconds, and the panel was severely damaged. The second discharge which extinguished itself had a high coulomb component of only 22.5 coulombs at a DC of 95 amp for 0.25 seconds; the substrate was slightly burned.

247-GP93-AR16W-0000 Figure A-50 August 17, 1970

This graphite panel was coated with aluminum woven wire fabric having a wire diameter of 8 mils and a mesh density of 60 x 60 per inch. The fabric was bonded to the substrate with BMS 5-29 adhesive, and no undercoating was applied.

Two 2-component lightning strokes with a high current component of 120 KA were directed to this coated panel. The first discharge had a DC level of 85 amp for 300 μs and the second discharge had a DC level of 125 amp for 700 μs; both discharges were extinguished by themselves. The second discharge yielded a severe damage to the substrate.

248-BR04-CR07C-0000 Figure A-50 August 17, 1970

This boron panel was coated with bronze woven wire fabric which had a wire diameter of 3.5 mils and a mesh density of 120 x 120 per inch. The wire fabric was bonded to the substrate with BMS 5-29 adhesive; and no undercoating was applied.

Two 2-component lightning strokes were directed to this coated panel. The first component for both strokes was 120 KA at a 15 KV discharge, and the second component delivered an 80 coulombs and a 60 coulombs discharge respectively at 125 amp for 640 μs and 150 amp for 400 μs.

No visible damage to the substrate was observed.

249-GP94-AR06C-KF03 Figure A-51 August 13, 1970

This graphite panel was coated with aluminum woven wire fabric over a 3-mil Kapton film undercoating. The wire fabric with a wire diameter of 3 mils and a mesh density of 100 x 100 per inch was integrally bonded to the Kapton film.

Two 2-component strokes were initiated to this coated panel. The first component for both strokes was 100 KA, and the second component had about 42 coulombs at 100 amp for 420 μs and 133 amp for 320 μs respectively. The arc was extinguished by itself.

The surface coating was severely pitted, but no damage to the substrate was observed.

250-BR05-AR06C-KF03 Figure A-51 August 18, 1970

This boron panel was coated with aluminum woven wire fabric over a 3-mil Kapton film undercoating. The fabric with a wire diameter of 3 mils and a mesh density of 100 x 100 per inch was integrally bonded to the Kapton film.

An artificial lightning stroke with a high current component of 120 KA at 15 KV discharge and a high coulomb component of 150 amp for 450 ms was directed to this test panel.

The surface coating was severely pitted, but no damage to the substrate was observed. It was found that the 3-mil Kapton film undercoating had greatly reduced the induced temperature on the back side of the substrate.

251-GP95-AR04Z-0000 Figure A-51 August 18, 1970

This graphite panel was coated with aluminum woven wire fabric having a wire diameter of 2 mils and a mesh density of 200 x 200 per inch. The wire fabric was integrally bonded to the substrate with no undercoating. A discharge with a first component of 120 KA at 15 KV and a second component of 88 coulombs at 192 amp for 1.5 seconds was directed to this coated panel. The substrate was severely damaged.

252-BR06-AR04Z-0000 Figure A-51 August 18, 1970

This boron panel was coated with aluminum woven wire fabric having a wire diameter of 2 mils and a mesh density of 200 x 200 per inch. The wire fabric was integrally bonded to the substrate with no undercoating. The same test setup as the last one for the previous panel was used for this test; however, the discharge current was only 75 amp and lasted only 330 ms to yield a total of 25 coulombs.

The substrate was not punctured; however, the very smoky surface showed that something was badly burned.

253-GP96-00000-0000 Figure A-51 August 20, 1970

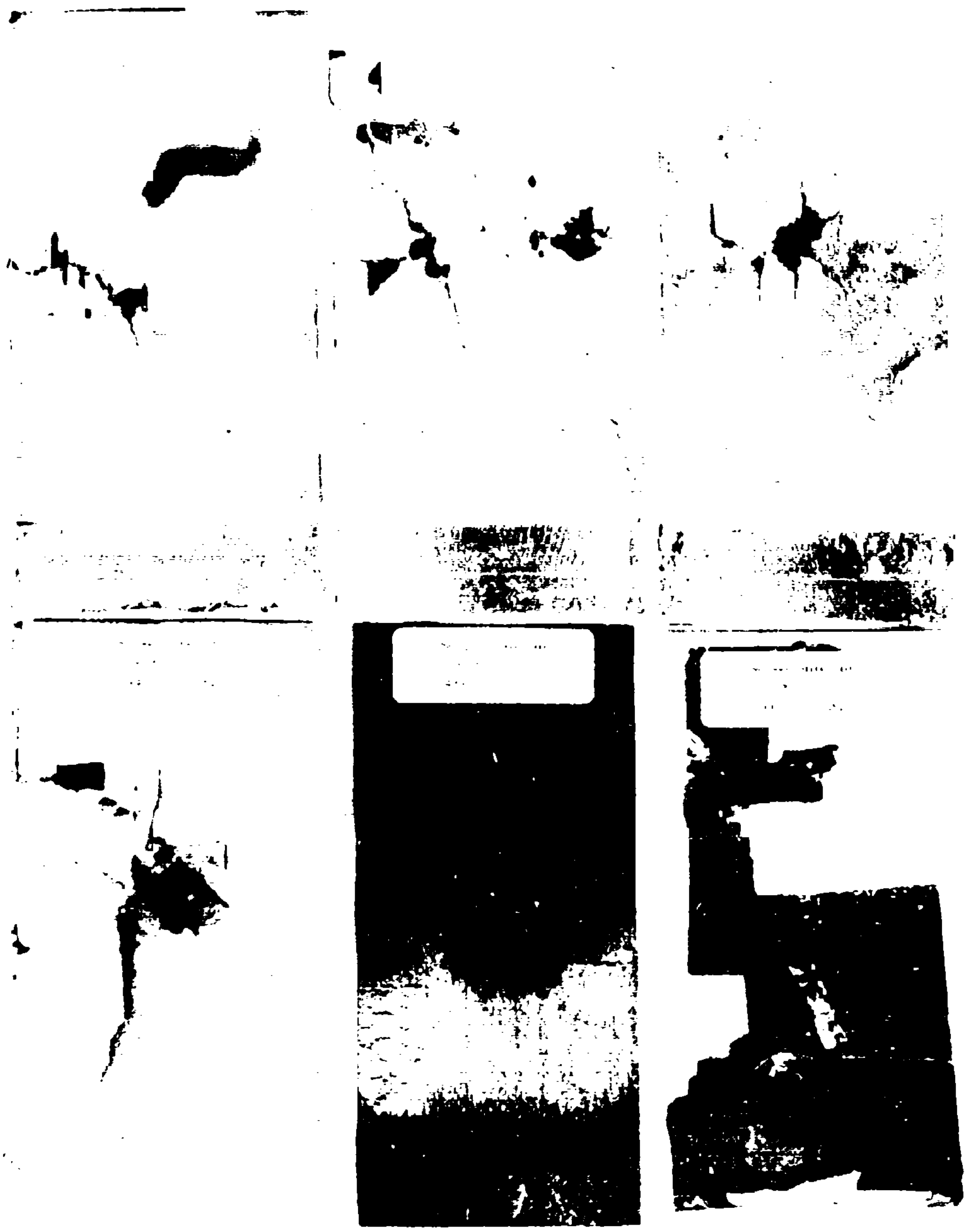
This was the first 12 inch by 12 inch size panel tested. This uncoated graphite panel was tested to verify the test setup for the final phase test of this contract; also, to find out how much damage to an uncoated substrate.

A 21 KV discharge was directed to this test panel. The current was 150 KA with a risetime of 12 μs and a duration of 24 μs.

The front surface of the substrate was badly burned.

254-BR07-DE07C-KF01 Figure A-52 August 20, 1970

This boron panel was tested before as the panel 190-BR77-DE07T-KF01; however, the diverter strips were taken away for the present test panel.



A 17 KV discharge was directed to this coated panel, the discharge current had a peak of 64 KA with a risetime of 23 μs and a duration of 40 μs. The substrate was severely damaged.

255-BR08-DE11C-EP05 Figure A-52 August 20, 1970
This coated boron panel was previously tested with the panel No. 200-BR83-DE11T-EP05; however, the diverter strips were taken away for the present test panel.

A 20 KV discharge was directed to this coated panel, the discharge had a peak current of 110 KA with a risetime of 12 μs and a duration of 24 μs.

The substrate was severely damaged.

256-GP97-DE10C-EP11 Figure A-52 August 20, 1970
This coated graphite panel was previously tested with the Panel No. 187-GP67-DE10T-EP11; however, the diverter strips were taken off for the present test panel.

A 20 KV discharge was directed to this coated panel, the discharge had a peak current of 98 KA with a risetime of 11 μs and a duration of 30 μs.

The substrate was severely damaged.

257-BR09-DE10C-EP11 Figure A-52 August 20, 1970
This panel was previously tested as the panel no. 186-BR75-DE10T-EP11; however, the diverter strips were taken away for this test.

A 20 KV discharge was directed to this panel, the discharge had a peak current of 90 KA with a duration of 38 μs and a risetime of 15 μs.

The substrate was severely damaged.

258-GP98-00000-0000 Figure A-52 August 20, 1970
A 30 KV discharge was directed to this uncoated graphite panel; the discharge had a peak current of 184 KA with a risetime of 10 μs and a duration of 21 μs.

The substrate was badly damaged.

259-BR10-00000-0000 Figure A-52 August 20, 1970
A 30 KV discharge was directed to this uncoated boron panel to yield a peak current of 175 KA with a risetime of 14 μs and a duration of 25 μs.

The panel was broken and damaged.

260-GP99-AR04Z-0000 Figure A-53 August 20, 1970
This graphite panel was coated with aluminum woven wire fabric which had a wire diameter of 2 mils and a mesh density of 200 x 200 per inch. The wire fabric was integrally bonded to the substrate with no undercoating.

A 20 KV discharge was directed to this coated panel, the current had a peak amplitude of 200 KA with a risetime of 11 μs and a duration of 20 μs.

No visible damage to the substrate was observed, and a surface flashover pattern was shown.

261-BR11-AR04Z-0000 Figure A-53 August 20, 1970
This boron panel was coated with aluminum woven wire fabric with no undercoating applied. The wire fabric having a wire diameter of 2 mils and a mesh density of 200 x 200 per inch was integrally bonded to the substrate.

A 30 KV discharge was directed to this coated panel, the discharge had a peak current of 200 KA with a risetime of 11 μs and a duration of 21 μs.

The surface coating was partially vaporized, and several small holes punctured by the stroke were observed on the substrate.

Figure A-53

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13. ABSTRACT

Coatings and coating systems were developed for protection of boron and graphite fiber reinforced plastic composites from structural damage by lightning strikes. The effectiveness of the protective capability of the proposed coating systems was tested with an artificial lightning stroke consisting of both high current and high coulomb components. The primary criterion of a successful coating was the capability of a test panel to sustain a simulated lightning discharge without structural damage to the composite substrate.

Numerous coatings or coating systems have been developed and evaluated. They can be classified into the following general categories: continuous metal foils; woven metal wire fabrics; knitted metal wire mesh; plasma and flame sprayed aluminum; metal pigmented paints; and nonmetallic pigmented paints with or without undercoatings. Several coating systems show protective capability with aluminum knitted wire mesh and aluminum woven wire fabric considered to be the most promising coatings.

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